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NATIONAL ACADEMY OF SCIENCES-NATIONAL RESEARCH COUNCIL

Division of Earth Sciences

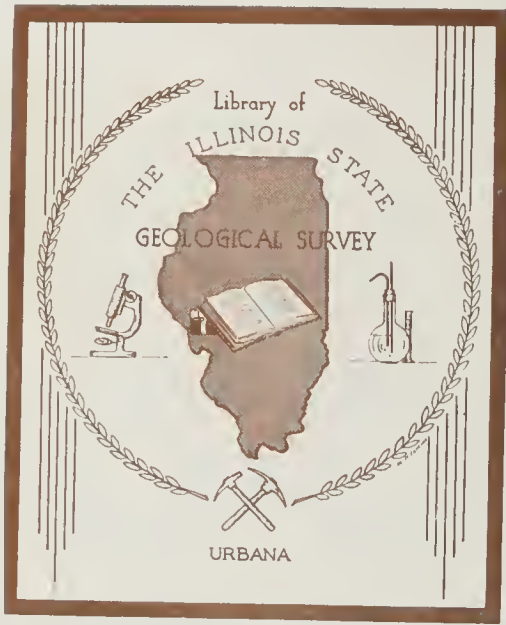
Committee on Geologic Aspects of

Radioactive Waste Disposal

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Report to the Division of
Reactor Development and Technology,
United States Atomic Energy Commission

May 1966



COMMITTEE ON GEOLOGIC ASPECTS OF
RADIOACTIVE WASTE DISPOSAL

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I. INTRODUCTION

The work of the Committee on Geologic Aspects of Radioactive Waste Disposal of the National Academy of Sciences-National Research Council (NAS-NRC) is supported by the Division of Reactor Development and Technology of the United States Atomic Energy Commission (AEC), whom the Committee serves as adviser. The Committee's responsibility to that Division is to observe and study critically the research and development activities of the Division with respect to radioactive waste disposals in the ground, and to provide counsel regarding the safety of the Division's current and proposed operations insofar as they are affected by geologic considerations.

The membership of the Committee has changed from time to time as earlier members were replaced by new ones. Of the present eight members, one has served on the Committee since its inception in 1955, and the three newest were appointed in March 1965. The professional backgrounds of the present members reflect a broad range of experience in the earth sciences. They are, respectively, hydrology, geohydrology (two members), radiohydrology, petroleum reservoir engineering, mining geology, structural geology and geophysics, and subsurface geology. *

Like all responsible citizens, the members of the Committee are concerned for the welfare of man and the perpetuation of an environment in which he can satisfy his physical needs and realize his cultural aspirations. The development of safeguards against hazards which might threaten the safety of man and his environment is therefore a prime desire of the Committee. In pursuit of this broad objective the Committee concerns itself with all phases of ground disposal of radioactive wastes, although its specific delegated responsibilities are the geologic aspects of the research and development program of the AEC's Division of Reactor Development and Technology. While this report, therefore, deals primarily with the several items of that program that are discussed in the chapter on "Research and Development Program of Division of Reactor Development and Technology," some observations on the general subject of radioactive waste disposal in the subsurface are outlined, with suggestions regarding research or other investigations which may be useful to personnel engaged in those activities.

II. HISTORICAL REVIEW

A. General

The Committee on Geologic Aspects of Radioactive Waste Disposal, first assembled in April 1955, originated as a steering committee whose

* See Glossary for meanings of unfamiliar terms.

principal function was to assist the AEC's Division of Reactor Development and its agents in a search for safe methods of ground disposal of hazardous wastes. From late 1955 until mid-1960 the Committee was known as the Committee on Waste Disposal; in January 1961 it acquired its present name.

In the beginning the Committee's specified responsibilities were limited to the disposal of high-level wastes, and in its conferences with other groups it was actively soliciting and evaluating ideas for any methods of disposal into the earth.

It early established for itself a set of guidelines which it continues to observe:

- (1) Safety is a primary concern, taking precedence over cost.
- (2) Radioactive waste, if disposed of underground, should be isolated as permanently as possible from contact with living organisms.
- (3) The disposal of waste is a special problem for each particular installation.
- (4) In addition to problems requiring urgent attention at existing plants, other problems will be created by the long-range development of power from atomic energy.
- (5) Selections of future plant sites must include consideration of waste-disposal sites and methods, waste transportation and other potentially hazardous operations. Study of a specific site requires complete geologic mapping as well as a combination of geophysical and geochemical studies.

B. 1955

In September 1955, the Steering Committee sponsored a conference at Princeton University (Ref: "The Disposal of Radioactive Waste on Land," NAS-NRC Publ. 519) at which 65 scientists representing many branches of earth sciences, biology and medicine, chemistry, physics, engineering, and other pertinent fields of knowledge, considered various problems of radioactive waste disposal on land and offered suggestions toward their solution. Among the proposed disposal methods which developed from this meeting were disposal in salt, deep-well disposal in permeable formations, and conversion of liquid wastes to solids. A conclusion of the Committee after reviewing the Proceedings of the Princeton Conference was that continuing disposal of low-level waste in the vadose water zone, above the water table, probably involves unacceptable long-term risks.

C. 1956

By the end of 1956, the Committee's activities expanded to include reviews of results obtained from research and development work carried out by the Atomic Energy Commission and its contractors, recommendations of necessary or desirable areas of investigation or specific projects, evaluations and recommendations regarding work proposal from responsible organizations, periodic reviews of operational experience, and assistance in the integration of available earth-science knowledge pertaining to waste-disposal problems.

D. 1958

One of the early results of the Committee's interest in subsurface disposal methods was the publication in July 1958 of a report, "Thermal Considerations in Deep Disposal of Radioactive Waste," by Francis Birch (NAS-NRC Publ. 588). Having considered the theoretical aspects of heat generation and dissipation from radioactive wastes that might be placed in deep permeable strata or in salt deposits, and after calculating the heat levels that would be reached, Birch concluded that

"The results suggest that nearly any quantity of waste producing heat at the rate of 0.01 watts per gallon, if distributed in a layer of the order of 100 meters thick, can be accommodated without undue rise of temperatures. Concentrations much above this level would raise questions exceedingly difficult to answer. It does not appear that any decisive advantage is gained by burial at excessive depths (greater than a few thousand feet, for example) provided that potable water supplies and other natural resources are adequately protected."

In October 1958, when its area of responsibility had been broadened to include low-level and intermediate wastes, the Committee considered a proposal to inject radioactive wastes under pressure into artificial fractures in shale. At that time the Committee expressed doubt that this injection procedure would always produce horizontal fractures but agreed that the concept should be tested in the field. Meanwhile, Oak Ridge National Laboratory (ORNL), in Tennessee, had initiated plans to investigate possibilities for disposal in salt beds, and on request from AEC a subcommittee in the Division of Production, American Petroleum Institute (API), had recently completed a report on "Problems in the Disposal of Radioactive Waste in Deep Wells" (October 1958). The NAS-NRC Committee endorsed API's proposed program of studies for deep-well disposal, involving ion-sorption studies on naturally occurring sedimentary rocks, plugging, and corrosion

and radiation damage, as well as regional geologic studies to highlight favorable areas for more detailed analysis. At the same time it expressed continuing concern about the disposal of intermediate and low-level waste liquids in seepage pits at ORNL because they contaminate the environment. It concluded that low-level waste is particularly amenable to disposal in deep porous media or possibly in moderately permeable shale, and it urged a long-range effort to find sites and methods of treatment so that these wastes can be emplaced safely at depth.

E. 1960

A proposal to construct bedrock storage facilities for high-level liquid wastes at the Savannah River Plant (SRP), South Carolina, was brought to the attention of the Committee in March 1960, it having first been submitted to AEC in 1958. Recognizing that the wastes must be contained indefinitely and that grouting, sealing or lining might be necessary, the Committee recommended that SRP proceed with test borings, and that the project then be reconsidered after the results of the tests were available. The Committee noted that the investigation should include study of the sedimentary section and hydrologic conditions above the basement, and that within the basement the studies should include the extent of fractures, water content and conditions, and the physical and chemical properties of the rocks.

The Committee commended the program of studies in hydraulic fracturing at ORNL and the progress on investigations toward deep disposal in salt, which project had progressed from the laboratory to field tests in a salt mine in Kansas.

During the same meeting the Committee expressed concern over the fact that no existing AEC installation is in a geologically acceptable location for disposal of highly radioactive liquid waste and that future waste-producing plants might also be placed in unfavorable locations if the feasibility of safe ultimate disposal is disregarded. The Committee also expressed its belief that there is serious need to get beyond the problems of disposal at existing installations that were located with little regard to ultimate disposal procedures, and to give additional emphasis to the job of finding safe permanent disposal sites.

In May 1960, the Committee visited the Carey salt mine near Hutchinson, Kansas, where ORNL was conducting its investigations on the feasibility of disposal in salt. Studies at that time were still being directed toward disposal of high-level liquids in salt, although attention was beginning to turn to development of a process for calcination of high-level liquid wastes in stainless-steel pots suitable for subsequent burial.

In view of increasingly unsatisfactory results of disposals into seepage pits at ORNL, the Committee reiterated its concern about that type of disposal, observing that similar disposal methods were being used at the National Reactor Testing Station (NRTS), Idaho, and at Hanford Atomic Products Operation (Hanford), Washington.

Still concerned about disposals into seepage pits, the Committee visited the Hanford and NRTS sites in June and July 1960. Its conclusion as a result of the visits was that neither location had been shown to provide safe and permanent disposal, although some confidence was expressed by the local staffs, based on the fact that the sites are located in areas of little rainfall. It commented that

"The protection afforded by aridity can lead to over-confidence: at both sites it seemed to be assumed that no water from surface precipitation percolates downward to the water table, whereas there appears to be as yet no conclusive evidence that this is the case, especially during periods of low evapotranspiration and heavier-than-average precipitation, as when winter snows are melted. At the National Reactor Testing Station pipes were laid underground without ordinary safeguards against corrosion on the assumption that the pipes would not corrode in the dry soil, but they did. At NRTS plutonium wastes (plutonium half-life 24,000 years) are given shallow burial in ordinary steel (not stainless) drums on the same assumption. Corrosion of the drums and ultimate leakage is inevitable.

"The movement of fluids through the vadose zone and the consequent movement of the radioisotopes are not sufficiently understood to insure safety. The work in progress is commendable and deserves encouragement. The mounting pace of nuclear developments will add to the pressures on waste disposal facilities, procedures, and research at Hanford and Idaho Falls, and the future emphasis should be on safe ultimate disposal viewed from the long range and with attention to a rapidly changing world."

F. 1961

The Savannah River Plant was visited by the Committee in December 1961, when four test holes had been drilled into the crystalline "bedrock" and the logging and testing of the first had been completed. At this early

stage of the investigations the nature and extent of fractures in the bedrock were not clear, and the hydrologic system had not yet been determined. In the general discussion, doubt was expressed that the ideal, absolutely dry, opening in the basement rock could be attained, and the problem of protecting fresh water from contamination loomed large. The Committee recommended that much more precise information on the amount, rate, and direction of movement of water in the area under consideration be obtained; types of recommended measurements and tests were specified; steps for obtaining more information on the orientation of structures in the crystalline bedrock were urged.

Reports also were heard on the progress of fracturing experiments at ORNL and on studies of various types of grout mixes. The Committee commended the present status of the project, but stressed the importance of learning the orientation of the hydraulically induced fractures. It further cautioned that the specific information produced by hydraulic-fracturing experiments in folded and faulted rocks of a heterogeneous sequence such as that at Oak Ridge cannot be extrapolated safely from one formation to another or from one area to another.

Further laboratory and field studies on the disposal of radioactive liquids in salt were reported, and the Committee learned that the project, which had been initiated soon after the Princeton Conference, was now being returned to the original objective of determining the phenomena that might be associated with the storage or disposal of solid wastes. The Committee was satisfied with the progress of the studies, and recommended that the effect of storing dry, packaged, radioactive wastes in a salt bed be tested as soon as possible.

Proceeding further, the Committee noted

"The containment of fission products in an inert solid is still the manner of waste disposal that the Committee most favors. Research and development designed to produce a material from which fission products cannot be leached should be encouraged and supported as long as there is a reasonable possibility of attaining the desired objective. Nevertheless, the Committee still supports the idea that liquid wastes may be disposed of with safety into deep synclinal basins, below the level of the lowest potable water."

G. 1963

At a meeting in Washington in June 1963, the Committee heard reports

regarding the Savannah River bedrock-storage proposal, the grout-injection experiments at ORNL, and the feasibility studies of disposal in salt; much time was devoted also to reports of studies of deep-well disposals in permeable formations. These are outlined in more detail in the following paragraphs.

SRP personnel provided the Committee with volumes of data that had been derived from $2\frac{1}{2}$ years of careful drilling and testing of exploratory boreholes. The ultimate objective of the research was to determine the hydrologic characteristics of subsurface sedimentary and crystalline rocks at the plant site and the various other parameters that, it was hoped, eventually would determine whether or not the crystalline bedrock would be a suitable reservoir for the storage of high-level waste liquids. The Committee commended the SRP staff on the progress that had been made in its investigations, and expressed its opinion that for long-term safety, underground disposal at this locality is much better than storage in near-surface tanks. The Committee also observed that much work remained to be done before the safety of a bedrock storage chamber could be demonstrated, and it offered suggestions regarding further steps that would be desirable. It recommended that work be started on the next phase of the program, and that SRP personnel visit existing mines in crystalline rocks of the Atlantic Coast piedmont in order to study the bedrock as exposed in mine openings and to observe some of the problems of water control in such chambers.

Progress in the development of technology for artificial fracturing and grout injections at ORNL appeared to be satisfactory. A number of experimental injections had been made, using simulated wastes, and the location, shape and extent of the resultant grout sheets had been determined. No evidence of vertical fractures had been found, and it was reasonably certain that the ideal of producing horizontal fractures had actually been attained. The Committee recommended initiation of a pilot-plant operation for disposal of actual low-level wastes as the next stage in the continuing experiments. Further, because of the danger of creating vertical fractures by high-pressure injections at depth, the Committee recommended that disposals be limited to the relatively shallow red-shale member of the Conasauga Formation.

Investigations toward disposal of high-level liquids in salt beds had been discontinued since 1961, and attention in the Kansas salt mines had been directed instead to the problems of storing high-level solids in salt. Experiments designed to determine the heat-diffusion characteristics of the salt beds and the effects of radiation on the salt were under way. Continuation of the studies toward ultimate disposal of high-level solid waste in salt was recommended by the Committee.

In connection with AEC's research program regarding disposal of liquid wastes by injection into deep permeable formations, the Committee heard reports on a series of studies of geologic basins initiated to select a site for pilot-plant injection operations in a deep disposal reservoir. Individual basin reports were being prepared by personnel of the U. S. Geological Survey (USGS), together with a summary report on all basins in the conterminous United States. Simultaneously a study of six basin provinces was being conducted by a subcommittee of the American Association of Petroleum Geologists (AAPG). The six provinces had been selected on the basis of geologic conditions in each province that might be suitable for three different types of underground disposal: (1) Shallow salt beds for high-level solids, (2) shale strata at depths suitable for injection of grouted intermediate-level wastes into hydraulically produced fractures, and (3) a deep permeable sandstone for injection of low-level waste liquids*.

Dr. W. J. Kaufmann described experimental work being conducted at the University of California where a group of injection and relief wells in a five-spot pattern within a 36-foot square plot of ground were drilled to depths of about 95 feet in a thin (3 to 7 feet) confined layer of unconsolidated sand and gravel. Studies had been made of the movement of tritiated water, of water containing Strontium 89; and of the radioisotope solutes themselves as their progress was retarded by sorption on the aquifer surfaces.

In order to extend the studies into deeper subsurface systems which might more closely resemble the deep permeable reservoirs toward which AEC had been looking for possible disposals, a field study had been proposed in which fluids would be injected into a permeable sandstone at a depth of a few hundred feet. A site for this purpose had been selected near Bartlesville, Oklahoma, where the U. S. Bureau of Mines would conduct injection tests in the Cottage Grove sandstone member of the Pennsylvanian Chanute Formation. The description of the stratigraphic section, as presented to the Committee, indicated that the objective sandstone is underlain by a coal bed. Inasmuch as the permeability of coal is likely to be fairly high, the Committee suspected that the coal would probably act as a bypass for injected fluids, in which event the experiment would fail. A somewhat deeper sandstone, the Wayside Member, was considered too thick for satisfactory experimentation, and because it is overlain by a limestone stratum of doubtful quality as a seal it was considered even more unsuitable. The Committee judged that

*The results of this study have been reported in "Radioactive waste-disposal potentials in selected geologic basins," USAEC Div. of Technical Information Report SAN-413-2 (1964).

although the proposed injection experiment per se probably would provide some of the desired results, the chosen site probably was unsuitable, and recommended that a more favorable geologic location be sought if subsequent testing confirmed this evaluation.

H. 1965

The present report of the Committee stems from a series of meetings that began on April 12 to 15, 1965, when the Committee visited plant sites at the Savannah River Laboratory, South Carolina, and at Oak Ridge, Tennessee. At Savannah River the Committee was briefed thoroughly on the present status of the investigation into prospects for storage of high-level liquid wastes in the Precambrian crystalline bedrock; it visited current disposal operations including the open seepage basins for low-level liquids, trash burial grounds, and the storage tanks for high-level liquids. All of the operations were discussed in detail during indoor sessions. Before leaving Savannah River the Committee also heard briefly from Dr. E. H. Baltz regarding present efforts by USGS to find a site suitable for subsurface injection experiments of the type attempted at Bartlesville, Oklahoma.

At Oak Ridge the Committee visited the site of grout-injection operations and learned of developments since its 1963 meeting. Downhole logging after one injection had revealed gamma activity above the grout sheet, which may have been the result of migration of the grout upward between the well casing and wall of the hole or may have been evidence of vertical fracturing; however, because formation water had flowed back into the hole after the injection, the gamma activity was more probably the result of contamination from that source. Additional briefings and discussions included studies of fixation of radionuclides on solids and in emulsified asphalt, the movement of nuclides in ground-water streams, the programs for converting high-level liquids to solids, and various current waste-management practices such as the use of seepage pits and trenches, the use of burial grounds for radioactive trash, the construction of an evaporator plant, and the monitoring of radioactivity both at ORNL and in the surrounding countryside.

On May 10 the Committee visited the Carey Salt Company mines at Hutchinson and Lyons, Kansas, to observe experimental work on storage of high-level radioactive solids in salt beds. It then travelled to Idaho Falls and Arco, Idaho, for a $1\frac{1}{2}$ -day review of research programs and operations at NRTS. Because of the large number of facilities and the diversity of operations at NRTS, the range of subjects discussed and processes observed was broad. The subjects included the ground-water hydrology of the Snake River Plain and the NRTS reservation, to which much time was devoted

during the visit; the need for a deep (5000-foot) exploratory bore-hole; tritium-tracer studies of the movement of ground water and injected wastes; ion-exchange phenomena; present disposal practices for both liquid and solid wastes of high, intermediate and low levels of radioactivity; monitoring procedures; calcination processes for conversion of high-level liquids to solids; and considerations of costs and economy.

Although impressed by the competence and dedication of the NRTS staff in its efforts to solve many vexing disposal problems, at the conclusion of its visit the Committee departed with two unrelieved major anxieties: (1) that considerations of long-range safety are in some instances subordinated to regard for economy of operation, and (2) that some disposal practices are conditioned on over confidence in the capacity of the local environment to contain vast quantities of radionuclides for indefinite periods without danger to the biosphere. These concerns will be discussed further in this report.

On May 13 and 14 the Committee examined disposal operations and installations at the Hanford Atomic Products Operation, Washington, and discussed research programs and operational practices with local staff. As at NRTS the spectrum of waste-disposal projects at Hanford is a wide one. Subjects that were discussed included the geology and ground-water hydrology of the Hanford site and the Pasco Basin; research in hydrology with respect to ground disposals at Hanford, both for saturated and for unsaturated flow; studies pertaining to anticipated changes in the hydrology after completion of the Ben Franklin Dam on the Columbia River imposes its influence on the ground-water levels; soil chemistry and mineralogy of the Hanford site; the migration of radionuclides in the subsurface, their monitoring and control; current waste-disposal practices for radioactive trash and low, intermediate and high-level liquids; progress in development of technology for calcination of high-level liquids and disposal of the solid products. Tours of the Hanford site enabled the Committee to observe various installations and procedures.

As at NRTS, the Committee was concerned over the prevailing belief that the unconsolidated soil, sand and gravel that comprise the surficial materials to a depth of several hundred feet provide a reservoir for safe storage of tremendous quantities of wastes of all levels of radioactivity, and that no hazardous amounts of radioactivity will percolate down to the water table. The inadequacy of present understanding of hydrology in unsaturated earth materials (the vadose zone) was generally recognized.

The Committee assembled in Washington, D. C., on June 7 to 9, primarily for the purpose of drafting its report to AEC, but it also took

advantage of an opportunity to receive further briefing on developments in AEC's deep-well disposal program, particularly the completion of the basin studies by USGS and AAPG. It also heard and considered a proposal for preparation of a subsurface reservoir that would be held in standby readiness in the event of an unanticipated release of radioactive gas from a plant accident.

Inasmuch as certain aspects of the report draft required further investigation and prolonged study by the Committee, another meeting was held on August 30 and 31, in Dallas. This was solely a discussion and work session, and the final drafting of this report has been done subsequently. The Committee's appraisals, comments and recommendations pertaining to the research and development programs and the waste-disposal practices that were reviewed in all of the 1965 visits and meetings are contained in the following pages.

I. Conclusions

Throughout the fabric of the 10-year history of the Committee's deliberations run some continuing threads of purpose and conviction. Prominent among them is the realization that none of the major sites at which radioactive wastes are being stored or disposed of is geologically suited for safe disposal of any manner of radioactive wastes other than very dilute, very low-level liquids, with the probable exception of grout injection into fractured shale at Oak Ridge. Another is the knowledge that the safety and the needs of populations in centuries to come demand that methods and facilities be developed now to receive and contain safely in perpetuity the volumes of wastes that will be produced as the nuclear industry expands and sites for new plants are selected and developed.

Research and subsequent development of promising techniques have provided a series of improvements in disposal methods that augur well for the handling of the larger amounts of radioactivity that are expected to be produced beyond the year 2000. These are bright strands in the warp through which are woven the observations and recommendations of the present report.

III. ACKNOWLEDGMENTS

As related in preceding paragraphs, during April and May 1965 the Committee was privileged to visit operations at five sites where radioactive-waste management practices are being developed, these being the Savannah River Plant (SRP), Oak Ridge National Laboratory (ORNL), the Lyons salt mine of Carey Salt Company, the National Reactor Testing Station (NRTS), and Hanford Atomic Products Operation (Hanford or HAPO). The Committee appreciates the hospitality and cooperation that were shown

by the staffs at all sites. They generously supplied copies of reports and data, and patiently answered a multitude of questions. Additional useful information has been provided by staff members of AEC and USGS.

1V. OBSERVATIONS

A. General

The Committee is favorably impressed by the competence, dedication and sincerity of all of the people in AEC and its contractor companies who are responsible for the safe handling of radioactive-waste materials. We are happy to acknowledge the conscientious efforts that generally are being applied to the problems of safe storage and disposition of hazardous materials. We particularly commend the progress on the solidification of the high-level and intermediate waste liquids, the extension of the program of disposal in salt to a field study, and the continuing developments in technology for disposal by grout injections.

In radioactive-waste disposals all plants operating under AEC surveillance are guided by the radiation-protection standards that have been developed by the Federal Radiation Council (FRC). These standards are defined specifically in reference to such terms as the Radiation Protection Guide (RPG), Radioactivity Concentration Guide (RCG), and Protective Action Guide (PAG). In operations that have been observed by or described to the Committee, efforts are directed toward restricting radioactivity to a fraction of the amounts permitted by the FRC standards.

The choice of treatment and disposal procedures for radioactive wastes is based not only on the characteristics of the radionuclides and the chemical and physical properties of the media in which they are contained, but also on the total amount of radioactivity in the wastes. A scale of radioactivity commonly used in AEC's Division of Reactor Development and Technology is the following:

Low-level: Less than one microcurie per gallon.

Intermediate: One microcurie to one curie per gallon.

High-level: More than one curie per gallon.

On the other hand, at each site the staff has established its own scale of levels of radioactivity in waste materials, and these are not entirely uniform from site to site. For example, intermediate-level wastes in some places may contain as much as 10 curies per gallon. Straub ("Low-level radioactive wastes," AEC Division of Technical Information Publication, 1964) cites a usage in which low-level wastes have activity measurable in micro-

curies per liter or per gallon, intermediate levels measurable in millicuries per liter or per gallon, and high levels in curies per liter or per gallon.

Another suggested "classification," adapted from other industrial operations, is based directly on methods of handling and disposal, rather than on a numerical scale of concentrations:

Concentrate and contain (high-level wastes).

Delay and decay.

Dilute and disperse (low-level wastes).

To the extent that consideration is given to the longevities of the various radioisotopes in the wastes, such a classification appears to be applicable to radioactive-waste disposal. It is, however, not a classification of wastes but rather a summarization of concepts for methods of handling them. All three concepts require isolation from the biosphere of radionuclides in hazardous concentrations. To "concentrate and contain" carries the stringent requirement that the container must be leak-proof throughout the period of hazard. Because artificial containers are subject to corrosion, fracture, and other forms of damage over periods of centuries, safe natural containers totally and permanently separated from the zone of fresh water must be used. To "delay and decay" requires that isolation from biosphere be complete during the period when hazardous concentrations exist. To "dilute and disperse" requires particular attention to the quantities of long-lived radionuclides in the wastes, especially in view of prospects that concentrations in the ground may increase cumulatively through the years, and that changes in soil chemistry or hydrologic patterns may release the sorbed nuclides. To the extent that radioactive decay exceeds input, there is no reason for alarm.

The Committee acknowledges AEC's awareness of the potential hazards of cumulative build-up of radioactivity from long-lived nuclides, as well as careful monitoring that is part of the routine at disposal sites to avoid such danger. The procedure includes recording of the amounts of all radionuclides in the waste streams, sampling and analysis of fluids obtained from monitor wells in disposal areas, and computation of activity held in the ground. The continuation and improvement of such procedures at all sites, including privately owned plants to be built in both the immediate and the far future, are anticipated.

In view of the hazards inherent in a cumulative build-up of long-lived radioactivity above or in a fresh-water aquifer after decades of a disposal operation, it might be well to consider the use of a scale of radioactivity based on the longevity of nuclides in the waste as well as on the concentration of activity.

B. Geology

1. Savannah River Plant

The Savannah River Plant occupies about 315 square miles in South Carolina, 20 miles southeast of Augusta, Georgia. The site lies in the Atlantic Coastal Plain physiographic province, near its inner edge where the wedge of coastal plain sedimentary strata is relatively thin. Intake areas for the fresh-water aquifers in the strata lie a short distance westward, the edge of the Piedmont province being only a few miles upstream from Augusta. The average annual precipitation is 43 inches. The topography is one of rolling hills with local relief as much as 250 feet; maximum surface elevations are about 350 feet above sea level.

The stratigraphic section has a total thickness of about 1000 feet above the Precambrian basement and consists of unconsolidated and partly consolidated sedimentary strata ranging in age from Upper Cretaceous to Recent. The thickest unit is the Tuscaloosa Sandstone (Upper Cretaceous), near the base of the sedimentary section. It consists of about 600 feet of gravel, sand and intercalated clay beds and contains the largest volume of fresh-water reserves in the area.

Between the Tuscaloosa Sandstone and the Precambrian rocks is a thin layer (average about 70 feet) of saprolite clay which presumably is a residual from decomposition of the Precambrian crystalline rocks and spread across the surface of the coastal plain as encroaching seas advanced across the area in late Cretaceous time. Although the thickness of the saprolite layer appears to be fairly uniform, data from boreholes reveal places where the layer seems unusually thin. The log of borehole (DRB-2) in the SRP test series failed to show any of the saprolite clay, but accuracy of the drillers' log has been questioned. There may be buried channels or broader openings in the saprolite layer which interrupt its continuity, but none have been revealed clearly by the sparse data from scattered boreholes. In view of the small area that would be occupied by a channel, and in the present stage of subsurface technology, recognition of the presence of old channels could come only through fortuitous circumstances in which more than one boring would by chance penetrate an identifiable "window" or hole in the clay layer.

Underlying the saprolite clay is the basement of Precambrian rocks which consists chiefly of foliated gneiss and schist with lesser amounts of quartzite and phyllite. The rock is fractured in varying degree, the upper sections being more highly fractured than deeper ones.

2. Oak Ridge National Laboratory

This plant site of 92 square miles, about 25 miles west of Knoxville,

Tennessee, lies in the Valley-and-Ridge physiographic province between the Great Smoky Mountains on the east and the Cumberland Plateau on the west. The topography within the site area is characterized by parallel asymmetric mountain ridges separated by valleys whose floors are rolling or hilly. Topographic relief between ridges and valleys is generally in the range of 200 to 350 feet; surface elevations are between 800 and 1150 feet above sea level. The average annual precipitation is about 47 inches.

Except for thin covers of Recent alluvium the surface is cut mainly in Cambrian and Ordovician strata, which form the bedrock both on the ridges and in the valleys. As elsewhere in the Valley-and-Ridge province the Paleozoic strata have been subjected to lateral compression to the extent that much severe folding and thrust faulting have occurred; the topography is mostly a reflection of the tectonic structures. Abundant jointing and other fracturing of competent strata, as well as bedding-plane slippages, are to be expected. Fresh-water supplies are found at relatively shallow depths in Paleozoic strata and locally in the Recent alluvium. Deeper waters are brackish or saline.

3. National Reactor Testing Station

The area enclosed within the boundaries of NRTS amounts to about 894 square miles lying in southeastern Idaho, some 30 to 60 miles west of Idaho Falls. It is semi-arid land, the average annual precipitation being between 7 and 10 inches. The physiographic province is the Snake River Plain, a subdivision of the Columbia Plateau, about 200 miles long from northeast to southwest and 50 to 60 miles wide. The east and south margins of the Plain are drained by the Snake River; elsewhere the drainage is largely centripetal, the surface water disappearing by a combination of evaporation and seepage into the ground in areas of topographic depression. Streams such as the Big Lost River entering the Plain from mountains on the west and north debouch into mud flats or prairie sinks.

The surface of the Plain, which at NRTS is about 4800 to 5000 feet above sea level, is generally flat or hummocky except that here and there are a few buttes rising several hundred feet, in one instance more than 2000 feet, above the Plain. The surface rock over large areas is black basalt of Recent origin; some flows are still fresh, unaltered by weathering, and bare of vegetation. Elsewhere the lava is covered by a thin veneer of soil derived from decomposed lava, gravel, alluvial or aeolian sand and silt, or in some places lake beds or playa deposits. Beneath the dark basalt are flows of older, paler, acid lavas.

The subsurface sequence of layered rocks, to an unknown depth, consists of lavas interbedded with pyroclastic and clastic sedimentary

strata. The basement under them presumably consists of indurated Paleozoic rocks similar to those that can be seen in outcrops in adjacent mountain areas. They probably are strongly folded and fractured. Some of the lava beds above the basement are remarkably porous and permeable; together with beds of sand and gravel they are the chief aquifers of the province. It is estimated from discharged data that more than 13,000 acre-feet per day of water flows through these aquifers under the Snake River Plain. The direction of flow is southwestward, and a large portion of the water appears again at springs along the Snake River at the southwest end of the Plain. A conspicuous local feature there, near Hagerman, is known as the Thousand Springs, where an estimated volume of 500 cubic feet of water per second gushes from a basalt layer that crops out in the escarpment 185 feet above the river level.

4. Hanford Atomic Products Operation

The Hanford site occupies 567 square miles in southeastern Washington about 30 to 50 miles east of Yakima on the Columbia Plateau. It lies in the Pasco Basin subdivision, a topographic depression between the Saddle Mountains on the north, Rattlesnake Hills and Horse Heaven Hills on the west and southwest, and the Blue Mountains of Oregon on the southeast. Within the site boundaries, surface elevations above sea level range from about 350 feet at the Columbia River to 600 feet at the base of the Rattlesnake Hills. Topographic relief within the basin is low, the surface being generally hummocky except for the ridge of Gable Mountain, in the north part of the site, which rises some 600 feet above the plain. Rattlesnake Hills, at the southwest edge of the site, have a maximum elevation of 3500 to 3600 feet above sea level.

In a broader view, the site is in a structural basin of southern Washington and northern Oregon which was filled in late Tertiary (Miocene and Pliocene) and Quaternary times with thousands of feet of lava, pyroclastics, and interbeds of continental gravel, sand and silt. The base of the layered series lies at an unknown depth more than 10,000 feet below the surface. The nature of the rocks beneath the volcanic series is unknown; presumably the basement rocks are highly indurated and deformed Mesozoic and Paleozoic rocks similar to those seen in outcrops at the margins of the Columbia Plateau. The interval between the basement and the base of the lava series is a matter of speculation as to thickness, lithology, age, and fluid content.

All permeable strata that have been tested, lava as well as sedimentary beds, are fresh-water aquifers. In spite of the semi-arid climate (between 6 and 9 inches average annual precipitation), the reserves of fresh water in this great thickness of aquifers are enormous, most of the supply being derived from adjacent mountain heights.

The lava series is overlain in large areas by beds of gravel, sand, silt, and volcanic ash which constitute the upper part of the Ellensburg Formation and the Ringold Formation, and these in turn by late Quaternary alluvium and lake beds. These beds above the lava series also are aquifers, in which porosity and permeability are adequate. They and the underlying, permeable lava flows and interbeds are being used as reservoirs for ground disposal of radioactive wastes.

5. Comparative geology

It has been pointed out by R. M. Richardson* that conditions at SRP and ORNL are alike in respect to the fact that the water table at each site is shallow (a few feet or tens of feet) and the distance from any disposal operation to a point of ground-water discharge is short (hundreds of yards); further, that NRTS and Hanford are alike in that the water tables there are deep (hundreds of feet) and the distances to points of discharge are relatively great (miles). The different conditions result from the difference between humid and semi-arid climatic regimes. The operations at Lyons, Kansas, are exempt from such considerations being restricted to salt beds far beneath fresh-water aquifers.

Another set of tentative similarities, subject to confirmation by deep exploratory drilling at NRTS and Hanford, also should be recognized. Geologic conditions at SRP, NRTS, and Hanford probably are alike in respect to the fact that the fresh-water aquifers at each site occupy a thick sequence of relatively undisturbed layered rock lying directly on a basement of less permeable, folded, faulted and fractured "bedrock." At Savannah River the water in the basement contains a total dissolved solids concentration of about 6000 ppm, in contrast to about 34 ppm for water in the overlying layered aquifers. In other respects also the two rock systems appear to contain different hydrologic systems. The layered rocks at Savannah River, about 1000 feet thick, all lie in the zone of saturation.

At NRTS and Hanford no borings have penetrated the complete thickness of layered rock, and the degree of folding and fracturing in the underlying basement is unknown. Likewise the presence of any aquifers above the basement is now known. The deepest boring in the Snake River

*"Significance of climate in relation to the disposal of radioactive waste at shallow depth below the ground," Proceedings of International Conference on Retention and Migration of Radioactive Ions through the Soil; Saclay, France, Oct. 15-19, 1962.

Plain (NRTS) is only 1500 feet deep, and the deepest in the Pasco Basin (Hanford) is 10,655 feet. Only fresh water has been found in analyzed samples from either province, and the depth to which fresh water extends therefore has not been ascertained at either place. Between the water table and the thin root zone is a zone of unsaturated basalt and unconsolidated sediments, the so-called "dry soil," or zone of aeration several hundred feet thick. Nothing is known about the water regimen in the basement rock, or about any possible flow barrier between the basement and the overlying layers.

At ORNL, on the other hand, the folded, faulted and fractured bedrock composed of distorted sedimentary layers, is near or at the surface and contains fresh-water aquifers. Only a veneer of loose sediments, also containing fresh water, lies above it.

In contrast to these four sites, there are large areas in the United States, particularly in the stable interior of the continent, in which fresh-water aquifers are separated from the basement by many thousands of feet of layered strata which contain saline waters and are not likely to be drawn upon for water supplies. It is in such areas that disposal of radioactive liquids into permeable subsurface strata can more firmly be relied on as a safe procedure.

The above similarities and distinctions point out the major characteristics of the geologic environments on which decisions regarding disposals at the present plants must be based.

C. Hydrology

At all sites the Committee noted insufficient knowledge of or, at least, too little consideration of the three-dimensional movement of water and contained materials in porous media. Usually it is the vertical dimension that is poorly understood, and in the establishment of flow paths and velocity of movement this dimension is highly important.

V. GENERAL PRINCIPLES

The deliberations of this Committee continue to be guided by the basic rule that concentrations of radionuclides in waste materials should not be allowed to appear in the earth's biosphere before they have decayed to innocuous levels. This concept requires assurance that during any storage or

disposal* operations hazardous amounts of nuclides are isolated from the biologic environment, and that upon completion of the procedures the nuclides will remain isolated as long as they might constitute a hazard. For some nuclides this requirement means isolation for periods of 600 to 1000 years, periods so long that neither perpetual care nor permanence of records can be relied upon. All supplies of potable** ground water, whether or not they are now being drawn upon, are considered as being part of the biosphere.

It is recognized that radioactivity in concentrations less than RCG is allowable, and within these limits the Committee has no concern. It is the possibility of cumulative build-ups of long-lived activity that may exceed these limits after continued use of doubtful practices, and the prospect of unforeseen concentrations in excessive amounts resulting from unexpected and uncontrollable alterations in the environments in future decades that the Committee wishes to guard against. In this report, terms such as "excessive amounts," "excessive concentrations," and "hazardous accumulations" are used with reference to excesses beyond the limits established by the Federal Radiation Council.

The economics of disposal and storage operations are of concern, but they are relegated to second-rank consideration, safety being the matter of first concern always.

All studies of waste disposal below ground level have borrowed heavily from the geohydrologic knowledge developed for the production of water from aquifers and the production of oil and gas from petroleum reservoirs. However, whereas the hydrodynamics of fluid production largely involve a concept of statistical homogeneity of the formations involved, the disposal of an insidiously dangerous waste involves the necessity of tracing or predicting its course through all the intricacies of the nonhomogeneities of these beds. Hydrodynamic concepts including dispersion, sorption, and erratic flow in all types of sediments and rocks in nature need development and documentation.

*As far as possible in this report the word "storage" means emplacement with the intent and in such manner that the materials can later be retrieved. "Disposal" means emplacement in a manner or location that renders them practically irretrievable. In practice the two words often are used interchangeably, especially where the intent is not clear or retrievability is uncertain.

**Here "potable" refers to the quality of water which is now being consumed or eventually may be consumed by humans.

Such problems are properly first studied in the laboratory, but some of them cannot be brought into the laboratory and all of them need checking in the field.

In view of the clear prospect for ever-growing production of atomic energy and therefore the probability of increasing output of radioactive wastes, the Committee believes that safe disposal procedures should be established now rather than at later stages of power development. Because perpetual care of hazardous wastes cannot be assured, storage and disposal procedures should be so designed that permanent safety is certain. At the same time, land areas, water supplies, and other resources that are appropriated for permanent storage or disposal of hazardous wastes should be the least quantities that are compatible with the prime objective of perpetual safety.

In the last analysis, it is the property of mobility of hazardous radio-nuclides in any fluid medium that baffles all who are concerned with safety of disposals. Operators will, therefore, continue to face dilemmas in waste disposal until hazardous radioactive waste is reduced to solid form in the smallest possible volumes. This is the concept the Committee favors above all others: a procedure of disposal involving concentration of radioactive solutions, their conversion to almost insoluble solids, and subsequent burial far below fresh-water aquifers in almost impermeable rock such as salt.

The present larger installations of AEC represent widely varying types of waste production and disposal. Anything learned at these sites will be of increasing importance in the future when waste-disposal problems will be magnified. AEC quite properly has considered that it has the responsibility of developing all types of reactors and of assessing the safety and economics of each type. We believe that it has also the responsibility of studying in detail all of the phenomena involved in the disposition of wastes to the environment, not only on the basis of assessing any known or suspected hazard, but more broadly on the basis of founding a discipline of waste disposal that will be of increasing importance in the future, especially when private operators may dispose of such waste and consequently the profit motive will become more prominent. We believe that there should be no phenomenon involved in any of the waste-disposal schemes that is not completely understood.

VI. RESEARCH AND DEVELOPMENT PROGRAM OF DIVISION OF RE- ACTOR DEVELOPMENT AND TECHNOLOGY

A. Disposal in salt

1. Introduction

Storage or disposal of radioactive wastes in underground cavities in salt deposits was discussed at the Princeton Conference in 1955, and in succeeding years this concept has been developed to a stage approaching operational use.

Definite advantages in this method of disposal are inherent in the unique physical properties of halite, the chief mineral in most natural salt deposits. The principal advantages are that salt is impermeable, soft, plastic, and easy to mine; in addition, it is an efficient natural shield against gamma radiation and is not associated in the earth with potable water.

2. Early research

During early stages the investigation involved disposal of high-level liquid wastes in salt caverns. Studies began with laboratory tests of the physical properties of halite and the effects of heat and atomic radiation on those properties. At the same time, theoretical considerations of heat generation in liquid wastes and of thermal properties of subsurface salt deposits in which the wastes might be stored, were examined by Francis Birch. Preliminary conclusions from these studies were that heat-transfer characteristics, shielding properties, and other parameters are suitable for the use of salt as a disposal reservoir, and that salt flow or creep as a result of heating or radiation would not be so rapid as to endanger storage operations in a cavern. Experiments on the radiolytic production of chlorine from salt indicated that no serious problems from this source in a mine would be expected.

Field experiments then were conducted in a disused mine of the Carey Salt Company near Hutchinson, Kansas, in which simulated acidic and neutralized Purex wastes were placed in salt chambers for periods of several weeks to months. Some cavity alterations resulted, but a more serious effect was the radiolytic production of hydrogen and oxygen. While studies of radiolytic gas production were continuing, the advent of techniques for solidification of high-level liquids led to diversion of the major effort toward experiments in the salt storage of these more manageable, solid, wastes. The first of these experiments were conducted in existing chambers, where tests were performed on the rate of creepage and the effects of heat on those rates.

The salt beds in central Kansas are of Permian age, part of the ~ Wellington Formation in the Leonard Series. The salt is closely associated with anhydrite, magnesite, dolomite, and shale. It consists chiefly of halite,

but polyhalite occurs in small amounts, and other accessory minerals are minor impurities. Widely separated thin layers of clay form dark bands up to one inch thickness in the otherwise pale salt rock.

Field research more recently has been transferred to a mine of the Carey Salt Company near Lyons, Kansas. The total thickness of the salt section here is about 300 feet, and the chambers excavated in the Lyons mine are about 1000 feet below the surface.

3. Current research

Preparations are being made in the Lyons mine, in a new chamber constructed for this purpose, to test the effects of heat and radiation in simulated operational procedures for the storage of solid wastes by the emplacement of irradiated fuel elements obtained from the Engineering Test Reactor at Idaho Falls. A pattern of seven holes will be drilled in the floor of the chamber, one in the center of the pattern and six in a circle around it, spaced five feet apart. The holes are to be one foot in diameter, 13 feet deep, lined and shielded, and designed each to contain two fuel elements in canisters. The assemblies will be replaced by fresh ones at six-month intervals over a period of two years. Supplementary heat will be provided artificially in order to maintain a temperature of 200°C as the heat from the fuel elements declines. This temperature is the selected maximum temperature desired, because naturally trapped moisture in the salt produces a shattering of the salt when temperatures approach 250°C.

In another part of the chamber a similar array of electrical heaters will be installed for the purpose of distinguishing those effects due to heat alone.

Further studies of creep or flow are being conducted by measuring changes in the shape and dimensions of mine pillars, walls, ceiling and floor. The measurements are obtained by the use of both internal and external gauges. Preliminary results indicate increases in flow rates with heating that conform closely to laboratory results. The initial rates of closure of mined openings are high but they decrease with time. Heating increases the rates markedly, the effect of elevating the temperature being essentially the same as that of increasing the pillar load.

Small amounts of water have been found in the heated holes in initial tests, the moisture presumably having been released from thin shale interbeds in the salt.

The experimental operations also include tests of equipment and methods for transporting and handling the radioactive fuel elements.

4. Conclusions

The Committee is in complete agreement that (1) the use of caverns in salt beds as permanent storage sites for high-level radioactive solids has promise of being successful and satisfactory, and (2) that the tests now underway and scheduled in the mine at Lyons are well planned and should provide the data required for guidance of future operations. This experiment is now largely an engineering project. Our only suggestion regarding the geologic aspects is that ORNL include a study of the behavior of shale interbeds that will be subjected to long periods of elevated temperatures and radiation, in order to anticipate possible changes in wall, ceiling, and floor conformation additional to those caused by creep and flow of salt.

B. Grout injections in shale

1. Background

The principal objective of this research and development project, first examined by the Committee in October 1958 and actively pursued at ORNL since then, is the disposal of intermediate-level waste liquids by mixing them in grout and injecting the mixture into artificially produced fractures in subsurface shale strata. The grout enters the fractures and spreads out in thin sheets, later solidifying in place.

As explained earlier in this report, the bedrock at Oak Ridge lies at or near the surface of the ground, and the shallowest permeable beds in it contain fresh water. The altitude of the ground surface here is about 800 feet above sea level, and in the disposal area the surface strata are part of the Conasauga Formation of Cambrian age. Directly under it is the Rome Sandstone, Lower Cambrian, which, owing to reverse faulting, lies on Chickamauga strata of Middle Ordovician age. All of the strata are folded and locally crumpled as well as faulted. The rock that was selected for experimental fracturing and injections is the Pumpkin Valley Shale Member in the basal part of the Conasauga Formation. At this locality it is about 300 feet thick and is first reached in the overthrust fault block at a depth of 700 to 1000 feet below the surface. It is overlain by thin limestone beds and these in turn by gray shale.

2. Engineering procedures

Preparation of a borehole for injection consists of drilling a hole through the injection formation, then lowering and cementing casing to the total depth. Prior to injection the casing is cut at the depth at which a fracture is desired, by directing against it, at high pressure, a jet of slurry consisting of sand in water. The horizontal slot thus cut in the

casing and into the rock wall of the hole is thought to provide the initial orientation of the ensuing fracture.

Water is then pumped into the hole at pressures exceeding that of the combined weight of the overlying strata, with the result that the shale is fractured. Success of the operation depends in part on the creation of horizontal rather than vertical fractures, inasmuch as vertical fractures might lead upward into permeable strata and provide channels of escape through which radioactive grout fluid could contaminate potable ground water.

The grout mix is prepared at the surface, where all of the injection equipment is housed in concrete cells as a safety precaution. It is then pumped into the borehole under pressures sufficient to drive it through the slot in the casing and into the newly created fracture in the shale. The grout spreads through the fracture, forming a sheet which extends outward around the point of injection. It then sets up into a hard solid in a period of a few days.

The most recent series of injection experiments at ORNL consisted of five separate injections through one well, of both synthetic and real wastes, of various types of grout mixes, of dyes or radioactive tracers for subsequent identification of the grout sheets, of various fluid-loss additives, and of ion-exchange additives. The depths of the five injections, in the order of operation, were respectively 945, 924, 912, 900, and 890 feet. Breakdown pressures, at which the shale became fractured in each case, ranged from 2150 to 3800 psi. The volumes of synthetic or real wastes mixed into grout and injected into the shale ranged from 27,300 gallons to 148,000 gallons per injection.

ORNL currently produces about 4,000,000 gallons of intermediate-level waste liquids per year. It is estimated that the evaporator which is now being constructed at the site will concentrate the wastes to a volume of about 400,000 gallons per year, and that this annual amount can be disposed of in two batches of 200,000 gallons each.

3. Post-injection research

Monitor holes drilled around the injection well provide information on the extent of the grout sheets. It has been found that in some instances the sheet bifurcates, one or more times, resulting in multiple sheets from one injection. One explanation of this behavior is that the leading edge of the advancing grout becomes dehydrated, owing to absorption of water by the shale, with the result that increased viscosity creates a dam against which the more fluid grout cannot move; the fluid then breaks through to another bedding plane. An alternative explanation is that multiple fractures were

produced by water under pressure and that the grout entered two or more fractures more or less simultaneously. Similarly, the grout sheet could divide at points of natural weakness in the formation, passing up or down along pre-existing fractures, and then propagating laterally along bedding planes. The field data suggest that all of these processes were operative in the ORNL experiments.

Further research involves measuring the amount of uplift of the surface of the ground resulting from insertion of several sheets of grout between beds of rock strata in the subsurface. The areal extent of each sheet is first determined in a general way by observing the arrival of the leading edge at predrilled monitor wells and also by drilling core holes in the area after the grout has set. The exact outline is impossible to obtain by this methods, and it may be presumed that lobes or fingers extend beyond the mapped area in places and that indentations likewise occur. This would be true especially where the lithology of the reservoir formation is uneven so that travel of the grout is free in one direction or place and impeded in another.

The mapping shows that in many cases in the Oak Ridge experiments the outline of a grout sheet is ovoid rather than discoid, and that it is eccentric to the point of injection. The shape and accentricity are presumably due largely to structural attitude or dip of the beds, in which increasing overburden weight downdip forces the grout to move updip.

A series of traverses by precise spirit-leveling of the ground surface across the area of injections was conducted, in order to determine the amount of uplift caused by each injection. It was found that the amount of uplift is generally equivalent to the thickness of the group sheet as observed in cores taken from post-injection borings. The area of uplift, however, is not identical with the area of the sheet. The rock strata apparently reacted as a semi-rigid crust, so that uplift commonly extends beyond the observed edge of the sheet. As would be expected from such behavior, the outline of the uplifted area has no lobes or indentations. Although the seams of grout that can be observed in core samples of the strata are generally only about 1/16 to 1/8 inch thick, the maximum uplift of the surface is about 1/2 inch. As the maximum invariably occurs at or near the injection well, it is assumed that the grout sheet there is about 1/2 inch thick whereas farther away, at the cored locations, it is thinner.

The relations between volumes of waste and the amount of uplift are indicated by the following tabulation of two injections selected as examples:

Volume injected (gallons)	Area of grout (feet)	Diameter of uplift (feet)	Height of uplift at apex (feet) (inches)	
97,000	700 x 250	1000	.014	.168
132,000	650 x 400	1500	.040	.480

The possibilities of damage that might be caused by repeated uplift of the ground surface around a single much-used injection well have been considered. As the amount of uplift increases cumulatively, presumably a position would eventually be reached at which structural damage would be caused to surface installations such as pipelines and buildings. Evaluation of this possibility is an engineering problem which the Committee is not prepared to discuss.

Another possible type of damage, more serious but also more difficult to appraise quantitatively in advance of its occurrence, is contamination of potable ground waters above the grout sheets when tension cracks, small faults, or other fractures are created in near-surface strata by stresses resulting from arching. This kind of damage is not probable, however, for in a vertical sequence of 900 feet of layered rock the distortion would probably be created by elongation, which presumably would result in normal faulting; the slippage would be of small displacement, leaving no open fractures. In contrast, the amount of vertical uplift created by the injections is trivial, where 100 injections in the same well would raise the surface only 50 inches.

4. Conclusions

Hydraulic fracturing of rock formations is widely practiced throughout the petroleum industry. Experience gained through this work has indicated that fracture orientation depends on naturally inherent local stress distribution and rock inhomogeneities which vary from one geologic environment to another. We now know that general statements regarding fracture behavior can be misleading. For example, although it was early recognized that bottomhole pressures equal to 0.6 or 0.7 times the overburden pressure would always produce vertical fractures, it was also held that horizontal fractures would always be formed if overburden pressures were exceeded in the well bore. Experience has shown that the majority of all induced fractures are vertical; there is probably little horizontal fracturing at depths greater than 1000 feet, and 50 percent of shallow fractures are vertical. Inasmuch as vertical joints produced by natural forces commonly occur even in areas of tectonic stability, the prevalence of vertical induced fractures must be anticipated. Each case and area must be evaluated individually in terms of rock characteristics and pressures required to produce various types of fractures.

A few examples of fracture-pressure relations in the field illustrate the preceding comments. At depths of 1300 to 1500 feet in the Anona Chalk, Pine Island oil field, Louisiana, only vertical fractures were produced at pressures exceeding overburden pressure. In Colorado, the Green River shale yielded only vertical fractures at depths of 100 to 200 feet and at pressures two to ten times the overburden pressure. Horizontal fractures were produced at 400 feet in the Athabasca tar sands in Alberta at two to three times the overburden pressure, but the fractures did not coincide with notches that were cut in the well bore. Thus, in any given field situation the formation of interest should be subjected to experimental fracturing in order to determine how it will respond to various bottomhole pressures. As apparently is the case at ORNL, certain formations with characteristic bedding-plane weaknesses will be amenable to horizontal fracturing at shallow depths. At the same time, however, some vertical fracturing should also occur, especially where pre-existing joints are present.

It must be emphasized, therefore, that the successful experiments at Oak Ridge are probably not duplicatable at all other sites, because of differences in geologic conditions from place to place. Local conditions should be investigated carefully and pilot tests conducted before a site and a shale formation are accepted for grout injection.

In the routine of monitoring the grout injections, continuous liaison should be maintained between waste-disposal personnel and the specialists at major industrial research laboratories where new subsurface engineering techniques are being developed. Technological advances in downhole logging and reservoir mechanics, such as the use of cement-bond logs and fracture-finding devices, should be exploited in subsurface disposal procedures. The use of tiltmeters to record minute changes in surface levels will help to map the distribution of grout sheets. Disposal technologists may well profit from early knowledge of new subsurface devices and methods.

C. Solidification of liquid waste

Several processes for converting high-level liquid wastes to solids have been investigated, and some have reached an advanced stage of development. Basically, the products of these processes fall into two categories, the calcines and the glasses or ceramics. These processes which have shown sufficient promise to warrant more extensive development are: pot calcination, fluidized-bed calcination, spray calcination, and the introduction of phosphate, borate, or silica to yield a glassy product that is resistant to leaching. Currently a Waste-Solidification Engineering Prototype is under construction at Battelle Northwest Laboratories (formerly Hanford Laboratories) where some of these processes will be tested under operating conditions with actual high-level radioactive wastes. To be demonstrated are the

pot and spray calcination processes and the production of phosphate glass and ceramics. Under present plans the solid products will be stored at the surface in stainless-steel tanks enclosed in concrete shells, and will be studied in order to determine their long-term stability.

The ultimate objective of the entire solidification program for high-level wastes is the production of a form of waste which can be stored safely, economically, and with the greatest security to mankind. The engineering aspects of the processes are not within the scope of this Committee's ability to evaluate, but the manner of disposal or storage of the end products is of concern to us to the extent that it involves the geologic environment. In this respect we are interested also in the stability of the product.

The Committee is favorably impressed with the whole solidification program, because it promises relief from the problems of storing and disposing of high-level liquid wastes at present sites where disposal into the ground anywhere near the fresh-water aquifers would be intolerable. We are especially hopeful about the glass or ceramic products, because they may be safe from serious leaching and, thus, from release of hazardous radionuclides, for periods of many centuries.

At the same time, the Committee does not favor the suggestion that high-level radioactive calcines may safely be stored above ground or at shallow depths and above fresh-water aquifers at existing plant sites as a permanent disposal. In our opinion such a disposal of high-level long-lived radioactive solids is contrary to the rules of safety which AEC has sought to establish for handling of radioactive materials. The emplacement of such hazardous solids in salt vaults after a suitable cooling period would appear to be an obvious requirement.

An alternate suggestion that high-level radioactive solids might safely be stored in tunnels constructed in hillsides in a desert environment cannot be accepted without thorough research and experimentation. Of particular concern here would be the travel of ground-water floods resulting from once-a-century catastrophic deluges.

D. Ion-exchange studies

1. General

Ion exchange and other sorption phenomena have been studied by research personnel at the various AEC installations with respect to both synthetic materials and natural minerals. The studies include not only evaluation of the usefulness of synthetic materials and natural ion-exchange minerals for predisposal waste-treatment processing, but also the determi-

nation of the ion-exchange characteristics of the earth materials underlying the AEC reservations and environs. The earth materials are best studied in situ rather than in the laboratory, because of directional phenomena resulting from lithologic variations from place to place. The studies concerned with waste-treatment processing reveal economic parameters which compare favorably with those of other forms of fixation that are being considered for predisposal processing of waste.

We concur with the investigators that ion-exchange materials may be useful as a means of removing radionuclides from low and intermediate-level wastes in order to permit waste water to be disposed to the environment. By ion exchange the radioactivity in high-level wastes also is fixed in a form for easy packaging as a recovery procedure in order to render the isotopes available for subsequent beneficial use. It should be noted that efficient sorbants that are completely or nearly saturated with radionuclides must be considered as intermediate-level waste and treated as such during ultimate storage or disposal.

In connection with direct disposals to the ground, it is emphasized that (1) where the exchange capacity of the soil or rock is high, constant watchfulness will be necessary in order to avoid excessive concentrations of radioactivity, and that the distribution pattern of the waste will not be known exactly; (2) where the exchange capacity is not high, channelization will take place, as in the basalt at NRTS. In either case future changes in groundwater composition or patterns of flow may desorb the radionuclides and move them -- an intolerable risk, or they will eventually proceed at excessive levels directly to the environment.

Ion-exchange studies of the earth materials underlying the four operating sites are in progress, and the Committee agrees with the investigators that in some areas much remains to be done. At no site have studies been completed on the distribution and exchange capacities of the reactive materials in the soils and the underlying consolidated or unconsolidated rocks, and thus there is not a full understanding of the sorption and fixation processes and rates of movement of radionuclides beneath the plant sites.

2. Savannah River Plant

The Savannah River Plant is located in a humid region having a complex drainage network tributary to the adjacent Savannah River. The site is underlain by about 1000 feet of partially consolidated sediments. Because much of the surficial material is sandy and admixed with kaolinitic soil or clay lenses, ion exchange can be over-emphasized as an important retardant of radionuclides at this site. Low-level wastes have been discharged to pits and streams. Abandoned pits have been isolated hydrologically

by clay caps and peripheral dikes. Radioactively contaminated solid trash is buried in shallow trenches about 20 feet deep under a soil cover. High-level wastes are neutralized and stored in steel tanks which are buried under 8 or 10 feet of soil. Several factors point to a potentially hazardous problem resulting from past and present disposal practices. Long-term hydrologic studies of the ground-water regimen at Savannah River Plant have not been made; therefore, predictions of the maximum (once-in-century) rise of the water table would be tenuous. At this site, with its shallow water table, an exceptional rise of the water table could easily cause invasion of the abandoned pits and trash-containing trenches. Radionuclides would then be subject to desorption and other forms of leaching that would permit them to be mobilized and carried into the regional ground-water system. A major failure of one of the high-level tanks would probably overwhelm the safety devices designed to cope only with small seeps or leaks.

3. Oak Ridge National Laboratory

At ORNL much research is in progress in the field of mineral sorption; emphasis currently is on "fixation" (irreversible) phenomenology as compared to ordinary ion-exchange processes. The value of these studies will be proven if an economical process is developed to remove large quantities of radionuclides from liquid wastes by fixation on material that can be safely and economically stored or disposed. Unfortunately, most of the natural minerals that are able to "fix" radionuclides commonly found in waste are uncommon in the earth materials underlying the ORNL site. However, it has been reported by ORNL that desorption of cesium from Clinch River sediments is so low under most conditions that it may be considered "fixed." Past pit disposals, unscheduled releases, and leaks from stored or transported material have saturated the ion-exchange capacity of some of the sediments and rocks for certain radionuclides in parts of the ORNL site. Ground water that is tributary to the Clinch River or to its tributary streams commonly contains substantial quantities of strontium⁹⁰ and rubidium¹⁰⁶. It was reported to the Committee that in the reach of the Clinch River between ORNL and its confluence with the Tennessee River, radioactivity measurements indicated that the gross radioactive burden of the bottom sediments was 2000 curies. Most of this activity is, in all probability, derived from radionuclides sorbed on the sediments. However, it is not known what fraction is actually adsorbed and what is immobilized by being held to particulate matter by some other mechanism.

Because ORNL, with a climatic and geohydrologic environment similar to that of the Savannah River Plant, has little in its environment to attenuate radionuclides except the ion-exchange capabilities of the system, here too disposal of waste to the environment should be discouraged. Limited ion-exchange capacity and hydrogeologic characteristics at these plants

prescribe that much of the environmental disposal capacity should be held in reserve as insurance for operational accidents or possible accelerated movements of radionuclides from waste previously disposed. It would appear that a systems analysis of the ORNL site, the Clinch River, and part of the Tennessee River is called for, in order to determine the waste budget of the entire system. In this way, the impact of radioactive waste on the biosphere from both the stationary ion-exchange media (earth materials at the site) and the mobile ion-exchange media (stream-bed sediments) may be appraised.

4. National Reactor Testing Station

The National Reactor Testing Station, Idaho, is underlain by basalt flows which include intercalated sediments and in large areas a surficial cover of alluvium. Some liquid wastes are released to the environment at the site through wells or into ponds. Radioactive trash and other low-level solid material are buried in slit trenches covered by several feet of back fill. Gross ion exchange beneath the site is thought to be small not only because of the limited amount of sedimentary material, both surficial and intercalated, but also because the basalt has been little altered to minerals having ion-exchange capabilities. Although some ground water is perched in both the sediments and the basalt, the top surface of the regional groundwater body lies entirely deeper in the basalt, the water table lying several hundred feet beneath the land surface. Thus, with transmissibilities in the basalt as high as 15 million gallons per day per foot and a maximum rate of travel time of 50 to 60 years to springs in the Snake River Canyon, it is imperative that dilution and decay of radioactive wastes be considered when evaluating the safety of ground disposal at this site. Storage basins using clinoptilolite or other ion-exchange material seemingly are very effective for removing radiocesium and slightly less so for removing radiostrontium to less than drinking-water standards. It would seem that this method should be encouraged for primary treatment of wastes and that the ion-exchange capacity of the earth materials should be reserved for emergency safety procedures.

5. Hanford Atomic Products Operation

The Hanford Atomic Products Operation is making studies for the use of ion-exchange both as part of its waste-processing practice and as a useful natural radionuclide retainer in the subsurface material at the site. Additional waste is now being disposed of directly to the ground. Most of this waste is discharged to and contained in the sedimentary Ringold Formation which overlies the basalt terrane in this area. The movement of the waste has been down gradient towards the Columbia River, but with a laterally spreading dispersion front. Careful monitoring of the movement

of this waste indicates that there has been some differential retardation of the various radionuclides by ion-exchange; tritium and ruthenium seem to have been the least attenuated. A problem may occur when this waste front breaks through at the river channel. After break-through, continued disposal to the Ringold Formation would sustain the volume of effluent to the river, but cessation of waste disposal to the ground would not necessarily alleviate immediately the problem of radioelement contamination of the Columbia River. The Ringold Formation could drain for years after ground-disposal practices have been stopped, but probably with a tapering-off of the volume of effluent. Any contributions of radionuclides to the Columbia River from subsurface effluents will have to be considered as part of the river burden when determining the one-tenth RCG at the nearest point of use. Should direct discharge of waste to the Columbia River be at or near the concentration restrictions that are determined by the downstream use, plant operations may have to be curtailed or other means found for disposal of the waste.

6. Conclusions

At all sites where continuous disposal of low-level wastes or frequent unscheduled releases to the earth materials underlying the site occur, there is always the danger of a build-up of concentrations in the soil and underlying rocks. An equilibrium may be established by balancing the rate of disposals with the rate of decay of radioactivity; continuous disposals beyond this rate could lead eventually to hazardous excesses of concentration, at which point the earth materials would no longer be a suitable disposal medium.

Future changes in the ground-water regimen through intensive agricultural irrigation or nearby construction of dams or other water-regulatory works may easily affect earth materials containing adsorbed radionuclides. Especially reactive will be the unconsumed irrigation water containing dissolved fertilizer components and biological refuse from plants and soils. Since ion-exchanged nuclides on earth materials are subject to reversible equilibria, under leaching conditions that may be superimposed by radically different water introduced into the system, there may easily be induced a removal rate that is much faster than the sorption rate. The future chemical condition of the soil and applied water is not always predictable, as man's requirements from his environment are likely to change in future years of land use in the United States.

E. Bedrock storage at Savannah River

I. The waste-disposal problem

High-level liquid wastes at SRP are alkaline, aqueous solutions

derived from the treatment of spent reactor fuels in chemical-separation plants. They are piped first into water-cooled tanks to remain there until the greater amount of heat from decaying radioactivity has been dissipated. Low-activity water is then evaporated and the condensate sent to seepage basins; the residue goes into uncooled storage tanks. The tanks, built of steel and concrete, are located below the surface of the ground, each one on a steel "saucer" which serves to collect small quantities of liquid in case of a leak in the tank. At present there are 24 tanks having a total capacity of 23,400,000 gallons.

After about eight years of storage for decay of the shorter-lived isotopes, a typical waste contains several inorganic sodium compounds, 0.1 to 10 curies per gallon each of strontium⁹⁰ and cesium¹³⁷, and trace amounts of plutonium and neptunium. Physically it consists of two fractions -- a supernatant liquid containing nearly all of the cesium and a sludge containing nearly all of the strontium, probably as an insoluble carbonate. Inasmuch as laboratory tests indicate that reaction between either an alkaline or an acid waste liquid and the rock of the basement complex would form a nearly neutral solution, it is assumed that after several years storage in a bedrock chamber the strontium would be in solution as a bicarbonate.

Strontium⁹⁰, with a 28-year half-life, and cesium¹³⁷ with a 30-year half-life, are the elements of hazard in these wastes, for a period of at least 600 years would be required for their decay to innocuous levels. Although no severe emergency has yet appeared in the tank-storage program, four lesser leaks have occurred in a little over ten years, and it is commonly agreed that safer permanent storage or disposal facilities are demanded. The concept of emplacement in caverns to be excavated in the basement rock under the plant site is currently a proposed solution to the problem. The engineering design would include the construction of a shaft through the sedimentary column and far enough into the basement rock to be clear of the upper interval of more highly fractured rock. Investigations to determine the feasibility of the method are being conducted by SRP personnel.

The critical factor in all of the investigations and in the Committee's discussions is the proximity of the basement rocks to the fresh-water aquifers which overlie them, the only separation between the two being approximately 50 to 100 feet of clay. Pertinent aspects of the geology of the proposed disposal site are described more fully in the following paragraphs as a prelude to further discussion.

2. Geology

Sedimentary strata that have been penetrated in various borings at the site have a combined thickness ranging from 877 to 972 feet. All

permeable beds in this stratigraphic section contain fresh water in various amounts and of various qualities; in all of them the water is potable. The Tuscaloosa Formation at the base of the section contains two aquifers separated by a layer of relatively impervious clay about 60 feet thick. The thickness of the upper aquifer is about 170 to 250 feet, the lower one about 200 to 270 feet. Large supplies of soft water, low in dissolved solids, are present in both Tuscaloosa aquifers; in fact these are the principal reserves of fresh water upon which the population of much of South Carolina and adjacent parts of Georgia probably will depend in the decades of the immediate future.

The clay aquiclude at the base of the Tuscaloosa Formation has a thickness in the range of about 20 to 40 feet. Beneath it is a layer of saprolite clay about 30 to 60 feet thick, lying directly on the crystalline rocks of the Precambrian basement. The average thickness of the two combined clay layers is about 70 feet. The saprolite is thought to be the product of weathering of the Precambrian surface rocks before the time of Tuscaloosa deposition, and presumably is a residual deposit; that is, it was essentially still in place when covered by the lowest member of the Tuscaloosa Formation as advancing seas submerged the area in late Cretaceous time. However, it is reasonable to suppose that some agitation, transportation, and then deposition of the surficial materials occurred as the shoreline moved inland across the area.

In actuality the thickness of the saprolite layer is probably not susceptible to precise measurement, as the boundary at the base is no doubt gradational. Proceeding downward, the lithology may be expected to pass progressively from "pure" saprolite clay into clay containing fragments of crystalline rock, into a zone of boulders separated by smaller rock fragments in a clay matrix, into "rotten" rock containing lesser and lesser admixtures of clay, and finally into more or less unweathered bedrock. A large boulder surrounded by products of decomposition, and being essentially a bedrock segment enclosed between vertical and horizontal joints in which decay had been accelerated by circulating meteoric water, would probably be logged as the base of the saprolite clay in drilling.

During its exposures to the atmosphere in Mesozoic time, the basement surface was a part of the seaward sloping coastal plain, across which flowed the streams that had their sources in the mountains to the northwest. The miscellaneous character of the bedrock probably led to the development of a dendritic drainage pattern very much like that in the present Piedmont province. The flow of the major streams maintained channels in which residual soils were not allowed to form, but which instead were filled by stream deposits such as sand and silt. Identification of such deposits in the base of the Tuscaloosa Formation by borehole data alone is difficult; for that matter, penetration of a channel deposit by an exploratory borehole would be largely fortuitous in the light of currently available evidence.

The topography of the interstream areas must have been similar to that of the present Piedmont province, uneven and hilly, and the crystalline rocks undoubtedly were exposed at the surface in some of the more prominent hills as well as in stream-cut banks. It is difficult to imagine an area of Precambrian outcrop in which a soil cover blankets the entire surface without a break. Recognition of the probable existence of buried channels and erosional knobs beneath the Tuscaloosa Formation in the coastal plain is critical to any interpretation of subsurface data regarding lateral continuity of the layer of saprolite clay.

The basement rock consists of gneiss and schist, both of which are foliated crystalline rocks, and lesser amounts of quartzite and phyllite. The upper portion of the rock complex is generally highly fractured and weathered, the degree of fracturing and decomposition becoming less with greater depths. Below the upper 200 or 300 feet the rock is generally more nearly whole, although fractures do persist to the greatest depths that have been observed. Some fractures are "hairline" cracks which can be detected in hand specimens only by the application of penetrating oils. Others may be a measurable fraction of a millimeter. In the case of faults, where the rock mass on one side has moved in relation to the rock on the opposite wall, they may be inches wide and filled with fracture rubble. No such fault-gouge or breccia zones have been recognized in the deep boreholes thus far at SRP.

Obviously the rate of flow of ground water through the fracture system should be expected to vary from place to place, depending on the width of the cracks and crevices, but over large areas a single rate may be computed. It is the hydrology of this flow system that SRP has endeavored to analyze by tests and observations in deep boreholes. Seven holes have been drilled to depths approaching 1000 feet below the top of crystalline basement rocks at the proposed excavation site. An eighth hole, near the Savannah River in the west corner of the SRP reservation, reached the basement at a depth of 690 feet and was completed at a total depth of 765 feet. A ninth, in the south part of the reservation, reached the base of the Tuscaloosa(?) Formation at 1218 feet; a core taken from the interval 1299 to 1313 feet, the total depth, is rock that has been identified as Triassic in age.

The southeastward or seaward slope of the pre-Cretaceous surface is revealed by the increasing depth of the base of the Tuscaloosa sandstone in that direction. The well logs also indicate increasing thickness of the Tuscaloosa Formation itself in the same direction, although exact stratigraphic correlation of the sand stone units above the Triassic sedimentary rock in the ninth hole has not been determined. Ground-water reserves are therefore assumed to increase southeastward toward indefinite boundaries

where the aquifers, becoming deeper, are more compacted and less permeable, the sandstone becomes more shaley, and the water is more saline.

3. Hydrology

a. Present status of investigation

A great mass of information has been accumulated concerning both the nature of the rocks and the hydraulic characteristics of the water systems in the sedimentary strata and in the underlying basement. In addition to the nine deep wells mentioned above, nine shallower borings have been drilled, in clusters of three at three different locations in the prospect area, as observation wells at various depths in the Tuscaloosa Formation. Data regarding water levels and their fluctuations have been recorded from all eighteen observation wells in addition to shallower water wells that are producing in the area, and estimates of permeability and flow rates in various zones have been made by computations from input and output volumes in pumping tests. Samples of fluids and rocks in the Tuscaloosa Formation and the basement complex have been analyzed for chemical and physical characteristics. As would be expected, fluid movements were found to be much slower in zones of essentially "unfractured" basement rock than at depths where conspicuous major fractures had been logged. At the same time, withdrawals from major fracture zones in one well affected water levels in other wells, indicating that the network of fractures contains a single hydrologic system throughout the observed portion of the basement.

Several groups of data, computations, and lines of apparently related evidence lead SRP to conclude that the hydrologic system in the basement rock is effectively separated from that in the Tuscaloosa Formation by the saprolite clay layer:

(1) The clay layer is essentially impermeable or only slightly permeable and is believed by the on-site investigators to be continuous and unbroken throughout the area of the SRP reservation.

(2) The hydraulic head in the basement aquifer stands about 20 feet higher than that in the Tuscaloosa Formation.

(3) Both chemical analyses and electric conductivity measurements show a greater content of dissolved solids in the basement waters (822 to 7140 ppm; 1250 to 9650 micromhos) than in the Tuscaloosa (39 to 65 ppm; 55 to 100 micromhos).

(4) Chemical analyses show different gas contents in the two aquifers:

	Total gas ml/l	Average composition (percent of volume)						
		N	He	A	O	H	CO	CO ₂
Tuscaloosa	0.1	93.2	0.00	1.09	4.14	-	-	1.61
Basement	0.6	91.0	6.0	1.1	1.1	0.3	0.4	0.2

Mapping of fractures in the basement, and calculations of the rates of water movements in both systems, coupled with the interpretations of the saprolite clay layer as an effective seal between the two, led to the following conclusions by the SRP staff regarding the safety of the proposed storage procedures.

(1) By the aid of the preliminary borings at a selected site for excavation it should be possible to place a storage chamber in a location that is not crossed by a major fracture.

(2) By only partially filling a storage chamber with waste liquid and then sealing it and thus creating locally a hydrodynamic low-pressure anomaly, the influence of the natural hydraulic gradient as a mechanism in moving the radioactive fluid out of the chamber would be delayed. In view of the slow movement of fluids in the "sound" rock in which the chamber is to be constructed, it is estimated that a delay of perhaps 100 years can be effected.

(3) Having escaped into fine fissures in the "sound" rock, the radioactive fluid will move at a rate which is calculated to be about 1.4 feet per year, or 840 feet in 600 years. At this rate, travel time to the Savannah River would be 30,000 years.

(4) If in its travel the radioactive fluid finds and enters a major fracture, its velocity then becomes something on the order of 7.2 feet per year or 4320 feet in 600 years. Travel time to the Savannah River would be 5500 years.

(5) If escape routes should lead upward into the Tuscaloosa Formation through an unsuspected path in the saprolite clay layer, the fluid would move downgradient in the Tuscaloosa at a rate computed to be 360 feet per year or a travel time of 100 years to the Savannah River.

(6) The above computations disregard the effects of ion-exchange, which would be relatively insignificant in unaltered basement rock, moderately effective in weathered rock, and substantial in the Tuscaloosa

Formation. Laboratory studies have been made to determine the ion-exchange characteristics of the various rock types in the Tuscaloosa Formation and the Precambrian basement.

SRP concludes that the delaying actions of the several "barriers" cited above are sufficient to make the proposed disposal method safe. The long travel times would render the radionuclides ineffective as hazards by the time the Savannah River is reached, and numerous impermeable barriers above the Tuscaloosa aquifers would protect surface drainage from contamination by fluids that might escape from the basement storage chambers.

Accordingly, a conceptual design has been developed for excavating a storage facility in the basement rock. It would consist of four 5,000,000-gallon storage chambers 1300 to 1700 feet underground, an access shaft, service facilities, and encased pipelines from the Separations Areas. The construction cost is estimated to be \$12,500,000, a unit cost of \$0.625 per gallon of stored waste. If the chambers are filled to only two-thirds of capacity, in order to create the negative hydrodynamic anomaly that has been suggested, the unit cost would be \$0.938 per gallon.

b. Evaluation of present hydraulic information

Much ingenuity in testing the systems and a great deal of thought in interpreting them have been demonstrated by the SRP staff. However, in the absence of readily available other methods, computations of transmissibility and of velocity of movement in the crystalline rock of the basement have been based on concepts which originated and were developed for homogeneous sandy formations ("granular aquifers"). Many anomalies in the reactions of the wells to pumping, earth tides, and atmospheric changes show that the concept is of doubtful validity in this application. Further, the concept for computation of velocity of the water in the fractured crystalline rock is based as an essential part on the potentiometric gradient between the prospective site of the shaft and the Savannah River. Knowledge of the water level in the Precambrian bedrock at the river is based on the water level in one well, in which it can be determined only with considerable uncertainty. The potentiometric map for the bedrock water, based in part on this water level, represents an unexplainable pattern of flow. In any future work all of the data that were used in constructing this map should be evaluated anew in the light of the overall pattern of flow that is implied.

With regard to the pumping test data, the use of the Jacob method by the SRP staff, in which only the constant and log terms in the expansion of the exponential integral or "well function" are used, is not justified because for these data the other terms in the expansion are significant. However, the inaccuracies in the computation of transmissivity and

storage do not appear to be serious in the present context. More seriously, the given data do not conform in detail to the theory of cylindrical flow in a quasi-homogeneous aquifer. In most wells there was a different rate of response in the early stages of pumping of DRB-6 than in the later stages.

All data from the pumping tests seem to indicate that the hydrologic system in the basement rock in the test area is completely or almost completely isolated from that in the overlying Tuscaloosa aquifer; the draw-down curves for the wells increase with time in rate of fall, relative to that required for cylindrical flow, instead of flattening as they should if vertical replenishment through the saprolite were taking place. However, so long as the characteristics of flow are not completely understood some elements of doubt remain.

Five types of information are available for the combined rock-water system in the basement:

(1) A model to serve as a criterion may be set up as a flow through a series of equally spaced plane fractures to account for the transmissivities observed during the pumping tests. Using values of transmissivities and thicknesses of aquifer that are acceptable for the data of the pumping test, the width of such a fracture, in centimeters, is in the order of $10^{-3} s^{1/3}$, in which s is the spacing of such fractures in centimeters. The porosity of such a system is $10^{-3} \times (\frac{1}{s})^{2/3}$. These data indicate fracture widths and porosity, for fracture spacings as follows:

<u>Distance between fractures</u> (Centimeters)	<u>Width of fracture</u> (Millimeters)	<u>Porosity</u> (Percent)
1	.01	.001
30	.03	10^{-4}
300	.067	2×10^{-5}
3000	.173	5×10^{-6}

These fantastically small widths must be increased somewhat for (a) increased length of path between points through an intersecting joint system, (b) irregular and probably rough walls in the actual fractures, (c) motion around places of contact of the walls, (d) perhaps electrical effects on the moving dissolved ions. The previously indicated porosities would be increased proportionately. Nevertheless it seems probable that the actual velocity of the water in the cracks in the crystalline rock would be much greater than that computed by the SRP staff because these small porosities apply to the "major fracture zones." A very interesting problem is also posed as to ion-exchange characteristics of such very small cracks, perhaps with mineralogically somewhat altered walls.

(2) With the reduction in head and pressure in the water in the fracture system during pumping, an equal pressure from the weight of the overburden is transferred to the rock system, and the strain pattern in the rock is changed. Some water is taken from storage owing to the expansion of the water and any change in the volume of rock that may occur owing to the shift in stress distribution. In hydrologic work with granular aquifers it is usually assumed that the overall thickness of the aquifer is changed by the shift in stress, and that the total volume of the sand grains is not changed. A fairly simple model results. In fractured crystalline rocks of very low overall porosity, the contribution of the expansion of the water to the "coefficient of storage" of the hydrologist, or to the "compressibility of the water and formation" of the oil-reservoir engineer, is comparatively small, and the deformation of the rock masses between fractures may be of great importance. This model is apparently more complicated.

(3) An increase in barometric pressure depresses water levels in wells. If none of the pressure was impressed on the water in the aquifer, the drop in water level would be equal to the rise in a water-barometer. The difference between the two represents the part of the barometric load that is imposed through the overburden on the water in the aquifer. In the case of a granular, confined aquifer, there is again a simple relation between the "coefficient of storage" and the "barometric efficiency" of a well, and one can be computed from the other, at least approximately. Again the model for a fractured crystalline rock may be more complex, but a proper interpretation may further indicate the characteristics of the fractures. Apparently about one-half of the barometric variation is transferred to the water in the rock system in the Savannah River wells, although apparently also there are some lag effects that may suggest other characteristics of the fracture system.

(4) The body tide of the earth produces a small strain in the rocks near the surface of the earth amounting to the order of 10^{-7} on the horizontal cross section. This tiny strain produces in all wells in confined aquifers a measurable fluctuation, in many wells concealed by larger fluctuations from other causes. In the wells that are in good connection with the fracture system in the Savannah River area (all but deep wells DRB-2 and DRB-7), the maximum fluctuation, at times of new and full moon, is about 0.3 feet. Because the tide is a cyclinical phenomenon those wells that are in poor connection with the joint system should theoretically show fluctuations with decreased amplitude and a lag in phase. DRB-2 has a maximum fluctuation of about .03 feet and seems to be about four hours out of phase. DRB-7 has a still smaller fluctuation, and its phase lag is difficult to determine.

The tides produce a definite small strain in the aquifer as against a stress due to barometric loading and a shift in stress from water to rock material during pumping tests. It is possible that an analysis of the three effects will give a clue to both the size and the distribution of the fractures in the main water-transmitting joint system.

A very peculiar perturbation of water level occurred during the pumping of wells DRB-3 and DRB-6 in the two tests involving pumping of these wells. Ostensibly these fluctuations are periodic, suggesting earth tides and probably barometric effects, but if so the effects are greatly magnified in the pumping wells, apparently amounting to a few feet in DRB-3 and ten feet or more in DRB-6. Unfortunately changes in the pumping rate were made during both tests and, especially in DRB-6, measurements of pumping rate and depth to water were made at erratic times during the day. However, the fluctuations do not correlate with the recorded data on pumping rate and water level. If such large fluctuations are indeed to be correlated with the deformation of the rock system by tidal and barometric change, apparently they can only be caused by a change in fracture width and consequently in permeability. The observed changes could be so explained in at least a simple model if the main fractures are spaced something in the order of 100 feet apart.

(5) The tracer test with tritium, for which data are not now available, should provide among other things an independent estimate of the total volume of fracture space between the two wells. Thorough investigation of the hydrologic system in the basement complex by tracer injections of tritium should be of great value in revealing the direction, extent, and rates of movement of fluids. Full use of this technique is highly desirable.

c. Recommendations for further hydrologic research

The combinations of all the above forms of data should indicate a consistent model for the hydraulic characteristics of the basement complex, and therefore the nature of the rocks and the fractures in them. Until such an analysis is made it will be difficult to know the sort of hydrology with which we have to deal.

In order to make the hydraulic data more meaningful, two things should be done. Continuous water-level recorders should be installed on all wells, including those with small piezometer tubes and the two deep piezometers at a distance from the closely drilled site. A microbarograph or other means of maintaining a continuous record of barometric fluctuations should be installed at the main drilling site. The regimen of barometric response and of tidal response should be determined for all wells and should be of primary importance in learning the nature of fracturing at all available test points.

The second thing to be done is to make another pumping test under carefully controlled conditions with great care to maintain the rate of flow within an accuracy of one percent. Readings of water level should be made in the pumping well at fixed times of the day with assurance that no errors occur. The test should be run at least through periods between full moon and new moon, and at these times readings of water level in the pumping well and flow should be made around the clock. Evidently a continuous recorder would be preferred.

In the previous tests, anomalies in the data were treated as nuisances to be disregarded in fitting the data to the concept of a granular aquifer. Another test should be made in search of anomalies that are due to the nature of fractured rock aquifers, and no anomalies that are due to faulty procedure can be tolerated. Wells can be used as geophysical instruments, and the fluctuations of water in them under known conditions are likely after adequate study to give a truer picture of the hydraulic system than do any of the conventional geophysical techniques.

4. Conclusions

The Committee recognizes with appreciation the intensive and intelligent work of the SRP staff on the problems connected with the bedrock-storage concept, but is still dubious about its demonstrated safety. The placement of high-level wastes 500 or 1000 feet below a very prolific and much-used aquifer is in its essence dangerous and will certainly lead to public controversy. Any demonstration of its safety must leave no shadow of doubt.

The Committee is divided with respect to the advisability of continuing the investigations toward bedrock disposal of high-level wastes at SRP. Those who favor continuance feel that the next steps should include:

(1) Re-analysis of all of the hydrologic data from the basement rocks on the basis of fracture porosity rather than by methods designed for analyses of granular aquifers.

(2) If the new analyses provide sufficient justification, the performance of new and more carefully controlled tests in existing wells as described elsewhere in this report.

(3) If analyses of data from the new pumping tests are encouraging, the drilling of several additional deep observation wells at locations where the excavation of shafts and vaults might be contemplated. At least four borings into the basement at any such location should be planned. Presumably the new drillsites would be chosen where the least

permeability in the basement rocks might be expected, as perhaps in the vicinity of DRB-2 and DRB-7, and eastward. The hydraulic characteristics of the rock-water system would be studied in these wells in the ways outlined in Chapter VI-E.

In drilling any new borings the shale and clay interval at the Mesozoic-Precambrian contact should be sampled and studied, particularly with respect to dissolved elements in extracted fluids at progressive levels in the interval. Also, sonic (acoustic) logs of the complete borings, from top to bottom, should be made at each drillsite, for use in evaluating the possibilities for a successful seismographic survey of the basal clay layer.

The value of tritium-tracer tests for empirical determinations of flow direction and velocity in the basement rock is emphasized again because of their immediate usefulness and accuracy.

The excavation of a shaft and chambers would provide the best evidence of the possibility of permanently leakproof chambers. The Committee reiterates its recommendation of earlier years that SRP representatives visit one or more mines in Precambrian basement rocks in the Piedmont province, in order to observe the water-entry problems in those places. It probably is pertinent also to point out that although the integrity of a mined opening as a leakproof chamber can be examined and evaluated, the construction of a shaft and chambers is not expected to add substantially to knowledge of the hydrologic conditions in the basement rock in sectors not contiguous to the excavations.

It is the opinion of the majority of the Committee that the prospect of storing high-level nuclear wastes safely in the crystalline rocks below the prolific Tuscaloosa aquifer is poor. Mining experience indicates that the amount of water developed in mines is much greater than that produced by wells in the same rocks, because mines intersect a much greater number of fractures and other water-bearing zones than wells of comparatively small diameter are likely to do.

There are several elements of indecisiveness in the present evidence for or against the safety of the proposed storage system. In the first place, rapid growth in demand for water can well lead within much less than 600 years to the need for heavy withdrawals of water from both Tuscaloosa aquifers.

In the second place, work on the hydrology of the bedrock has been based largely on methods developed under the concept of the homogeneous granular aquifer. Many anomalies in the hydrologic data thus far obtained confirm the a priori doubt that such a model can be trusted when applied to fractured crystalline rocks.

Thirdly, any slow leakage from the bedrock system into the much greater flux in the Tuscaloosa Formation would almost certainly be unrecognizable by chemical means. The difference in helium content between the two systems, for example, may be due to the inability of analytical methods to detect minute amounts of helium that might enter from the basement rock into the Tuscaloosa Formation, there to be promptly swept downstream. A similar observation may be made with respect to the differences in salinity. The greater amounts of nitrogen, oxygen, and carbon dioxide in the Tuscaloosa water may simply reflect a greater intake of air in recharge areas.

Fourthly, the difference of only 20 feet in hydraulic heads between the systems above and below the saprolite clay layer at the observation wells is insufficient evidence to prove complete effectiveness of the clay barrier throughout the area of basement rock which could become contaminated by escaped radioactivity. The hydrologic data, if correctly interpreted, reveal conditions at and near the test borings, but at short distances down-gradient, the direction in which contamination would move, different conditions may exist. There may even be an area in which no clay layer separates the two aquifers. A widespread grid of observation wells would be required to map the hydrologic systems to the extent required for complete safety.

A much more rapid and less expensive mapping technique exists and might aid in establishing the continuity of the clay layer. Currently available data are insufficient for determining its usefulness in this application, but the needed data can be obtained during any future drilling operations. The technique is high-frequency seismographic exploration, a geophysical tool which has been used successfully by the petroleum industry (See Chapter VI-G, "Geophysical studies at NRTS"). It consists of measuring the depths to lithologic interfaces between rock layers of contrasting acoustic velocity characteristics by means of a high-frequency acoustic signal that is emitted from a source at the surface or in a shallow borehole. The time interval that is required for the acoustic energy to be reflected or refracted back to the surface is recorded, and the distance travelled by the high-frequency wave is computed from velocity data that were obtained previously from borings in the area of exploration. At depths of 900 to 1000 feet an interval of perhaps 30 feet containing rock of sharply contrasting velocities, as between firm sandstone or granite on the one hand and soft shale on the other, can be measured. The technique requires precise work with closely spaced "shot holes," using the best equipment. In this manner the position of the top and base of the clay layer might be determined at many closely spaced locations. If the basal contact is gradational, at least a minimum figure for thickness can be obtained.

In order to determine the suitability of the technique for application to the problem at SRP, it is necessary to have at least one complete sonic

(acoustic) log of an uncased borehole, from the ground surface to a depth that is well into unweathered basement rock, for the purposes of (1) learning the amount of velocity contrast between the clay layer and both the sandstone above it and the crystalline rocks below, and (2) determining the velocity of the entire rock column through which the seismic energy will travel from the surface to the basement and return. Obviously several complete sonic logs would be desirable in order to obtain average velocities and to learn what variables might be anticipated. Unfortunately the only sonic logs now available are those that were run below the casing in the intervals of basement rock in six of the deep observation wells.

Shot holes and seismometer holes drilled with a small rig might be expected to cost about \$1.00 per foot. An area of perhaps four square miles probably could be mapped at closely spaced intervals in about two months by an experienced crew at a cost in the neighborhood of \$25,000 per month.

F. Deep-well disposal

1. General considerations

Although disposal of liquid waste by injection into deep permeable formations has been considered for several years, important aspects of the subject have not been clarified. Rather, essential principles have been submerged in details which have slight significance to the over-all picture.

The term "deep" refers to any reservoirs in rock, not soil (see Glossary), which are below and so isolated from fresh-water aquifers that injected radioactive liquids will not obtain access to the aquifers either by natural means or by any process that is induced by the injection. In this context, we think of permeable sedimentary rock layers several thousand feet deep (generally at least 3000 feet) in geologic basins, confined above by thick relatively impermeable strata such as shale or salt deposits. Ideally, reservoir space that is suitable for deep-well disposal should be vertically restricted and laterally unrestricted.

Insofar as they could be determined with available data, the subsurface geologic conditions at all of the plant sites visited by the Committee fail to meet the specifications stated in the preceding paragraph. At the same time, the Committee has never entertained the thought of using deep permeable formations as reservoirs for off-site disposals. Questions of transportation costs and safety engineering, therefore, do not enter into the Committee's considerations of deep-well disposals for radioactive wastes. The method is assumed to be a candidate for application to disposal problems only at suitably qualified sites, and in this

light it is hoped that its advantages will be weighed carefully and applied as criteria in the selection of new plant sites.

All pore space in a permeable subsurface rock such as a layer of sandstone is occupied by naturally occurring fluids, principally water (commonly brine) but in some places petroleum oil or gas or nonhydrocarbon gas. The fluid may be static or may be flowing, but in a tectonically stable basin at depths of several thousand feet, where we are dealing with indurated rock instead of loose soil or unconsolidated sand, the rate of flow is rarely more than about three feet per year. In 1000 years, therefore, under natural conditions a fluid would not move as far as one mile. In most instances the geologic basins that would be considered for deep-well disposal of radioactive wastes have dimensions ranging from tens to hundreds of miles in width. The natural flow is, therefore, insignificant and does not enter into computations in the following discussion.

2. Present status of research

At present the subject of primary concern when considering deep disposals is the eventual fate of the introduced radionuclides -- where will they go, and how fast? The answers to these questions are being sought in some of the research programs that have been supported by AEC. One such study is an early one at ORNL, in which a slab of carefully selected Berea sandstone, having as nearly as possible uniform porosity and permeability, was treated as a laboratory-scale injection reservoir. A five-spot system of injection and relief wells was used to study flow patterns and rates and the dispersion of radionuclides. The movements of radioactive tracers were monitored at grid points in the 6' x 6' x 6" slab. In addition, the effects of ion exchange were studied in a cylindrical core of the sandstone 10 inches long and 1.75 inches in diameter.

Similar experiments, but on a larger scale in the field, have been conducted at the University of California and were planned at Bartlesville, Oklahoma, as described above under the heading HISTORICAL REVIEW.

Following the Bartlesville investigation, an attempt is now being made to find a more suitable site for such field tests. For economy and ease in acquisition, a site on federally owned or controlled land is preferred, and the following basic geologic requirements have been specified for the experiments: A flat-lying homogeneous clean sandstone, confined between impermeable strata in a structurally uncomplicated area; thickness between 5 and 50 feet; depth between 250 and 1500 feet; porosity between 10 and 30 percent; permeability between 160 and 1500 millidarcies. The objectives of experiments here will be to study under field conditions the possibility of determining the velocity of the radionuclides relative to that

of water, to study temperature effects, and to learn the extent of possible plugging of interstices by precipitates or by the swelling of clay particles resulting from any incompatibility between injected fluids and the natural fluids or minerals in the injection reservoir rock.

3. Hydrologic considerations

A deep permeable reservoir contains brines having, in most cases, greater salt concentration than sea water. The composition indicates that fresh water has had only limited or no access to these reservoirs even during geologic periods of time. Nevertheless, the geologic configuration of any reservoir and the pressure pattern (pressure gradients or, more correctly, potential gradients) of the contained fluids should be well understood before it can be used to dispose of radioactive fluids. Furthermore, there should not be a chance that the brine will be produced either for its mineral content or as a byproduct of any associated petroleum. In addition, the disposal process itself should not cause the fluids to gain access to potable water reserves, either behind or through the casing in the disposal well or through fractures in overlying impermeable formations.

The mechanics of disposing of radioactive fluids in reservoirs differ from those for the disposal of any other fluid only in the precautions necessary to prevent escape of radionuclides from the system, and thus it is not only feasible but also highly desirable to use information that is available from the experience of various industries in the deep subsurface disposal of salt water and other liquid wastes.

The pressure required to inject fluids into a permeable formation creates the necessary space capacity in three ways: (1) it compresses slightly the native formation fluid, (2) by exerting stress on the surfaces of pore walls it causes the rock formation to expand slightly, and (3) more importantly, it artificially stimulates movement of the formation fluids. As such a flow is radially outward, the highest pressures and pressure gradients are around the point of injection. When injection is stopped, the pressure increase disappears because a slight outward movement is sufficient to accommodate the expansion of the fluids and the contraction of the rock to their original condition. The relation between injection rates, pressure increase and the various parameters of the formation and fluids is well understood and will be discussed later in this chapter. The major source of difficulty lies in the collection and proper interpretation of geological and geographical data which will define the characteristics of the permeable reservoir that is being considered for injection.

• The disposal of fluids in any subsurface reservoir stratum is accomplished only by moving both those fluids and the displaced connate

fluids through finely porous rock, an operation which demands the application of energy, sometimes in large amounts. The required pressure is always in excess of the natural pressure of the formation fluids, the realization of which leads to a rather widely held belief that injection of large quantities of liquid waste would require pressures in the well bore of such magnitude that not only the reservoir rock but also the confining impermeable formations would be fractured. Experience in the petroleum industry has deepened the understanding of the flow of slightly compressible fluids in porous formations and has shown ways to minimize the pressure increases that are needed for the injection of liquids at high rates. Because of their importance in evaluating the concept of deep-well disposals, we shall discuss these pressure relations in some detail.

It is well known from theoretical considerations confirmed by practical observations, that in disposal systems the increase in pressure is directly proportional to the injection rate and to the viscosity of the liquid, and inversely proportional to the thickness of the formation and to its permeability. Taking these relations into account, in addition to the fact that the fluid is slightly compressible, the pressure effects of an injection rate of 500,000 gallons per day are illustrated in the following hypothetical example. The table shows the increase in pressure at the sandface and at various distances from the well at various times after injection was started. The results have been computed using the formation and liquid characteristics listed below and are collected in Table I.

Sandstone formation thickness = 50 feet
Permeability = 500 millidarcies
Porosity = 30%
Undisturbed reservoir or aquifer pressure = 2500 psi
Depth to injection reservoir rock = 5000 feet
Viscosity of injected fluid = 0.5 centipoise
Diameter of well bore = 6 inches
Compressibility of rock and fluid (relative to
volume of fluid) = 7×10^{-6} vol/vol/lb/inch²
Transmissibility = 1025 gal/day/ft.
Coefficient of storage = 45×10^{-6} (dimensionless)

The table shows that the major portion of the increase in pressure on the sandface occurs during the first day after injection was started, and that this pressure increases slightly less than 40 pounds for each ten-fold multiple of time. The table further shows the pressure increases that can be expected to occur in the disposal formation. It will take 274 years (100,000 days) and an injection of 50 billion gallons of liquid before the pressure at the sandface increases from 2500 to 3017 pounds. It is clear from this behavior that it will take an additional 2740 minus 274, or 2466

TABLE I

Pressure increase in psi after days indicated
and at various distances from well

<u>Distance</u> <u>(miles)</u>	<u>1</u> <u>day</u>	<u>10</u> <u>days</u>	<u>100</u> <u>days</u>	<u>2.74 yrs.</u> <u>1,000</u> <u>days</u>	<u>27.4 yrs.</u> <u>10,000</u> <u>days</u>	<u>274 yrs.</u> <u>100,000</u> <u>days</u>
1	0.5	19.0	55.4	94.6	134.0	173.8
2	0	4.3	32.6	71.0	110.4	149.9
3	0	0.8	20.5	57.1	96.4	136.0
5	0	0	8.2	40.1	79.0	118.4
10	0	0	0.5	19.0	55.4	94.6
15	0	0	0	9.2	41.8	80.7
20	0	0	0	4.3	32.6	71.0
30	0	0	0	0.8	20.5	57.1
40	0	0	0	0.1	13.0	47.4
50	0	0	0	0	8.2	40.1
60	0	0	0	0	5.0	34.2
75	0	0	0	0	2.3	27.3
100	0	0	0	0	0.5	19.0
125	0	0	0	0	0.1	13.3
150	0	0	0	0	0	9.2
Pressure increase in well, at sandface	318.5	358.1	397.7	437.4	477.0	516.6
Total volume in- jected (MM/gal)	0.5	5	50	500	5,000	50,000
Area flooded (acres)						
Displacement effi- ciency 100 percent	0.1023	1.023	10.23	102.3	1,023	10,230
50 percent	0.2046	2.046	20.46	204.6	2,046	20,460

years for the pressure on the sandface to increase another 40 pounds. Also, after 274 years the pressure in the formation one mile away from the disposal well will have increased by 173.8 pounds, about 1/3 of the increase that is observed at the well itself.

Very generally, the natural subsurface formation pressures, measured in pounds per square inch, are 0.45 to 0.48 times the depth in feet. Where, in the example cited in Table I, we mentioned a pressure of 516.6 pounds at the sandface after 100,000 days of injection operations, it should be kept in mind that this pressure is in excess of the natural undisturbed pressure in the reservoir of 2500 pounds and that only this amount of pressure increase is available for fracturing the rock. Once injection ceases, the pressure increase disappears almost as fast as it had begun, for the simple reason that from that moment the only movement of fluids in the formation is that resulting from expansion of the fluids and contraction of the reservoir void space. Because the expansion coefficient of both the fluid and the void space are small, only a little movement is required to reduce the increased pressures.

Table II shows the decay of the pressure increase in the well at the sandface, if injection is stopped after the number of days indicated. Within 24 hours after injection is stopped the pressure at the sandface is reduced by more than 300 psi, regardless of how long the injection has been going on.

The thickness, porosity and permeability used in the cited example may be higher or lower than found in the selected disposal reservoir. The effect of lesser porosity is to increase inversely the area to be flooded by the stated volume of fluid. Lesser permeability would increase the pressure that would be required to inject the fluid at the specified rates. Inasmuch as each characteristic can have a value that is different from the one used in the example, the number of combinations is great but their effects can be computed. The values found at each site will have to be considered when appraising the merits of the reservoir for disposal of fluids.

In oil-field operations, the objective of artificial fracturing of oil or gas reservoirs is to improve the permeability of the rock in order to increase the flow of oil or gas to the well opening. At the same time it is desired to avoid the loss of oil or gas through leaks that might unintentionally be created in the overlying or underlying impermeable formations. No reports of such leakages have been found in the technical literature of the oil industry.

Artificial fracturing is accomplished by the application of pressure through a column of fluid in the well, thus creating either vertical fractures,

TABLE II

Effect of discontinuation of injection on sandface pressures (psi)

(Injection rate 500 gallons per day. Sand characteristics as in Table I.)

Injection continued for (and then is discontinued)	<u>1</u> <u>day</u>	<u>10</u> <u>days</u>	<u>100</u> <u>days</u>	<u>1,000</u> <u>days</u>	<u>10,000</u> <u>days</u>	<u>100,000</u> <u>days</u>
Pressure increase in well at sandface at moment injection stopped	318.5	358.1	397.7	437.4	477.0	516.6
Pressure increase in well at sandface (psi)						
1 day after injection stopped	11.9	41.2	79.4	118.8	158.4	198.0
2 days after injection stopped	7.0	30.8	67.6	106.9	146.5	186.1
4 days after injection stopped	3.1	21.5	56.0	95.0	134.6	174.2
10 days after injection stopped	1.6	11.9	41.2	79.4	118.8	158.4
20 days after injection stopped	0.8	7.0	30.8	67.6	106.9	146.5
40 days after injection stopped	0.4	3.1	21.5	56.0	95.0	134.6
100 days after injection stopped	0.2	1.6	11.9	41.2	79.4	118.8

which usually occur at pressures that are about 0.7 to 0.9 times the weight of the rock overburden, or horizontal fractures, which are expected to occur at pressures in excess of overburden weight; exceptions to the rule have been observed. As the estimated weight of the overburden is commonly about one pound per foot of depth, the rock pressure in the example in Table I is about 5000 psi. Hence, the injection of fluids at a constant rate for 274 years into the described hypothetical reservoir would raise the pressure hardly enough to fracture the reservoir rock.

Upon discontinuance of the artificial pressures, the force exerted by the weight of the overburden will close the fractures, thus, in oil-field operations, defeating the purpose of the artificial fracturing. In order to avoid this result, coarse sand is injected along with the fracturing fluid, and the sand serves as a propping agent to hold the fractures open. Fracture treatments using from 25,000 to 50,000 pounds of sand are considered to be normal. The vertical extent of fractures can be observed by mixing the sand with short-lived radioactive material and logging its position by means of down-hole sensing devices. Experience in oil fields is that most of the fractures die out a short distance above the permeable reservoir.

In the case of deep-well disposals of radioactive wastes, it is clear that even if some fracturing occurred during injection operations, such fractures, unless artificially propped open, would seal themselves when injections are discontinued. Pressure increases which become excessive can be brought back to normal by interrupting the injection procedures as long as required.

Precautions such as the monitoring of bottom-hole pressures during injection, and surveying the hole with fracture-detecting instruments after test injections of nonradioactive fluids, can assure control of the operations, even where it may be desirable to fracture the reservoir rock purposely in order to improve injection rates.

As for the danger of fracturing the confining impermeable formations, it has been demonstrated that vertical fractures that are induced in petroleum reservoirs do not penetrate adjacent soft formations which have a high Poisson ratio relative to the reservoir rock. Fractures will propagate, however, through adjacent formations that are hard and brittle and have a low Poisson ratio, as exemplified by some dense limestones and quartzites. A requirement for a suitable disposal site, therefore, is a thick layer of soft rock such as shale or salt between the injection reservoir and any permeable aquifer or reservoir which is to be protected from invasion.

These discussions indicate that disposal by injection at high rates places a lower limit on the weight of the overburden and, hence, on the depth that is safe for containment. The weight of the overburden of a formation 1500 feet deep is about 1500 pounds; because the normal reservoir pressure would be about 700 to 750 pounds, only 300 to 400 pounds of additional injection pressure would lie within the margin of safety which would allow pressured injections without fracturing. Generally, the permeability of the formations decreases with increasing depth. The two desiderata oppose each other, and a compromise must be worked out on the basis of the known characteristics of all permeable formations which occur in the stratigraphic column at a prospective location. Proper site selection and preparatory studies can assure safe injection procedures where large volumes of liquid can be disposed of at relatively low pressures.

4. General industrial experience

Several examples of subsurface liquid waste injection are cited in U. S. Bureau of Mines Circular 8212, "Subsurface disposal of industrial wastes in the United States," by E. C. Donaldson, 1964. * Cited injection

*Another recent publication of interest is U. S. Public Health Service Publication No. 999-WP-21, "Deep-well injection of liquid waste," by Don L. Warner, April 1965.

rates and pressure behavior in consolidated and unconsolidated sedimentary rocks are generally similar to the data in Table I. Various chemical and mechanical treatments of the waste liquids facilitate trouble-free injection, and periodic treatments of the reservoir rocks are employed to remedy blockages caused by pore-plugging agents. The treatments are used routinely in oil-field brine disposals as well as in other industrial applications. Injected fluids should be chemically stable, bacteriologically sterile, and, where necessary, rendered nonreactive with respect to formational matrix and liquids. Inasmuch as the swelling of clay materials is fairly well understood, and techniques for its prevention have been developed, an examination of the permeable formations that are to be used for disposal will dictate the requirements that the injected fluid should meet in order not to cause plugging.

Reviewing the foregoing paragraphs, it can be stated that a large amount of injection technology exists that may be utilized in the deep-well disposal of radioactive waste liquids. Extreme care in the application of familiar techniques will, of course, be required. The particular reservoir conditions encountered, and engineering considerations that are unique to nuclear waste disposals, such as corrosion problems, safety measures, and programs for well reconditioning, will be the factors determining how this technology can be exploited. Engineering procedures for the necessary safety measures must be developed under the guidance of engineers who are experienced in deep subsurface operations.

For counsel and advice concerning questions of mechanical engineering in the construction, maintenance and rehabilitation of disposal wells, the Committee recommends appeal to the Society of Petroleum Engineers (Executive Secretary Mr. J. B. Alford, 6300 North Central Expressway, Dallas, Texas) of the American Institute of Mining, Metallurgical and Petroleum Engineers. The Society's membership includes petroleum and mechanical engineers who are experienced in procedures and problems in oil-well cementing and in various formation treatments such as artificial fracturing and acidizing.

5. Conclusions

The Committee believes that, given a satisfactory geologic environment in the deep subsurface and the careful development of engineering procedures that will prevent escape of radionuclides during transit from the surface to the disposal formation, it is safe and feasible to inject radioactive liquids into deep permeable rock formations. It must be clearly understood that our concept of deep-well disposal does not permit any disposals by injection into formations that directly underlie fresh-water aquifers, or anywhere near them stratigraphically. Nor does it allow injections under such conditions that lateral flow through the disposal reservoir would bring waste fluids into the zone of potable water in the same formation. Disposal operations

should be conducted sufficiently far from the rim of the basin, under such hydrodynamic conditions and at such great depths that accidental fracturing of an overlying formation would still not endanger a fresh-water aquifer. Where thousands of feet of strata including soft shale or salt overlie the disposal reservoir, no contamination of the biosphere could occur.

Considering the prospect that disposals of general industrial liquid wastes into deep subsurface formations will become more and more common in future decades, we foresee the likelihood of mutual interference by expanding circles of pressure influence from several disposal operations in the same reservoir formation. If three or four operations are conducted simultaneously in one disposal reservoir, even though the points of injection should be 50 or 100 miles apart, it can be seen from Table I that in a period of a few decades the areas of pressure increase will meet. Eventually the pressure increases will travel back to the injection wells, and the rates of increase will gradually accelerate. Certain limitations might then have to be imposed on further injections. These will not be great immediately but will increase as injections continue. The prospect requires that complete and accurate records be kept of pressure data in the injection wells and in observation wells that will need to be drilled for that purpose. Legal restrictions of multiple usages of reservoirs having prior demand may some day be necessary.

In the same line of thought, competition for available reservoir space also would dictate that any waste liquids should be concentrated as much as possible before injection. In the case of radioactive wastes, this would mean the injection of intermediate rather than low-level wastes, in which the limit of concentration would presumably be dictated by considerations of heat dissipation in the subsurface.

We return now to the subject of the proposed field experiments, such as the one which was attempted at Bartlesville, which are designed partly to learn about the relative velocities of water and radionuclides in an injection operation, and we reiterate our position that no deep-well disposals should be undertaken under conditions where injected liquids might under any circumstances reach the biosphere. In view of the logical presumption that radionuclides will travel no faster than the liquid which contains them, we see little need for the further expenditure of funds to study the relative velocities of radionuclides and water as any part of a deep-well disposal program. The value of such studies is limited in application to procedures in which it is anticipated that the waste liquids will remain in the biosphere or will return to it before the nuclides have decayed to a harmless level, as in disposals in soil. Insofar as studies of heat dissipation and of pore-plugging are concerned, this information is pertinent to deep-well disposal, but because of local variations in lithology

from place to place, the most useful results can be obtained by pilot operations in the selected deep disposal reservoir at an actual plant site.

G. Geophysical studies at NRTS

1. Geological background

The National Reactor Testing Station, in southeastern Idaho, lies on the Snake River Plain, which is both a topographic basin and a structural depression. Paleozoic rocks crop out in mountains to the north and are overlain by upper Tertiary (Pliocene) volcanics, apparently without any intervening strata. Lying on the Tertiary volcanics is the Snake River group of basalt flows and interflow sedimentary deposits. The surface is a veneer of alluvial, lacustrine, and aeolian deposits, except where basalt and other volcanic rocks are exposed.

The character of the basalt ranges from dense to vesicular to blocky. Some of the basalt flows are excellent aquifers, others are essentially impermeable. The total thickness of the basalt series exceeds 1500 feet, this figure being the maximum depth that has been reached to date in borings. The associated sedimentary deposits, similar to those of the surface veneer, are gravel, sand, silt, and clay, the porous and permeable beds among them also being aquifers.

The surface of the plain ranges in elevation between 4800 and 5000 feet above sea level. The water table descends from an elevation of 4600 feet at the northeast to 4400 feet at the southwest. The unsaturated interval, or zone of aeration, is therefore 200 feet to at least 600 feet thick. This is the interval of so-called "dry soil" above the water table which NRTS utilizes as a reservoir for the disposal of radioactive waste liquids.

Neither the depth to relatively impermeable basement rocks nor the depth to the base of the fresh-water zone, the collective group of aquifers, is known; only fresh water occurs in the deepest hole that has been drilled to date. The continuous need for more detailed and more accurate data regarding the distribution, capacity and interrelation of aquifers in the Snake River Plain led to a program of geophysical surveys, both by borehole logging and by ground and aerial mapping.

Data obtained from borehole logs are to some extent supplementary to information derived from laboratory analyses of samples, but when such data are properly interpreted they also provide additional information which is not otherwise obtainable. The methods of geophysical mapping provide interpretations of the regional configuration of various subsurface layers of rock. In areas of complex strata, such as the NRTS, the interpretations

are imprecise at best, and in the absence of supporting data obtained directly by drilling they are highly speculative.

Thorough evaluations of geophysical operations cannot be made in brief examinations such as those afforded to the Committee during its rapid tour of the sites last spring. This statement is particularly true of geophysical mapping, in which much depends on the amount and quality of basic data and on the manner of their day-to-day applications. Minor questions of geophysical-log interpretations were discussed at the sites, and the Committee's overall reaction to the work is favorable. The staffs appear to be competent and well informed. Following is a brief summary of the geophysical methods that were discussed, together with an annotated list of other techniques which might some day be useful.

2. Borehole logging

Techniques included under this heading involve the lowering of mechanical, electrical, electronic, radiation-sensing, or other instruments into a borehole for the purpose of making a continuous record or log of the physical properties of the rocks or fluids throughout the full depth of the hole.

a. Electric log -- The instrument records two basic parameters in boreholes filled with fresh (nonsaline) drilling muds: the spontaneous potential (s. p.) and the resistivity of the rocks to the flow of electric current. It cannot be used in a cased hole or in one which contains no water. In oil-field operations it is widely used and relied on for correlations of rock strata from hole to hole, and for estimates of qualities such as porosity, permeability, and fluid content in the rocks. As pointed out by operating personnel at NRTS, the electric log is of only minor value in southeast Idaho because both fresh water and dense basalt are highly resistive, and the resulting log lacks character.

b. Gamma-ray log -- This instrument was designed to detect and measure the amount of natural gamma radiation in the rocks that were penetrated by the drill. It can be run successfully in either cased or open holes, either wet or dry. Its usefulness is found primarily in the distinction and identification of different gross lithologies and, therefore, for stratigraphic correlations from hole to hole. At NRTS it is useful in the identification of such lithologies as basalt, tuff, and shale. It is important for operators to bear in mind that such interpretations need confirmation by the examination of drill cuttings in selected boreholes, not too widely spaced, in order to avoid misinterpretations as lithology varies from place to place.

• A more obvious use of the gamma-ray log in radioactive-waste disposal operations is in the detection of introduced gamma radio-

activity in the subsurface and, therefore, in mapping the extent of contamination in aquifers.

c. Density log -- The density logger is a device in which a gamma-ray source and a shielded detector are held against the borehole wall. The tool measures the induced gamma-ray intensity in the wall rock, a function of the formation density; porosity may be estimated from these data. Many corrections must be applied to the log readings, because the instrument is highly sensitive to mud-cake, and to borehole roughness (rugosity), and gas content of formation liquids. Density logs are more dependable in high-porosity formations (greater than 10%) than in low-porosity rocks. The effects are based on diffusion processes, and assumptions are made that all interactions measured take place in the formation and not the borehole. Further, natural gamma radiation is not counted or is negligible.

A new "compensated-density log" has been introduced by Schlumberger Well Surveying Corporation which is said to correct automatically for hole size and mud-cake thickness. Used in combination with other logs, the density log can give a fairly reliable indication of rock porosity.

d. Caliper log -- As the drill penetrates various layers of hard and soft rock, compacted or loose, fractured or whole, the diameter of the hole varies because of varying bit action or caving of the walls. The caliper log is made by a mechanical device which measures continuously the diameter of the hole. Used partly in conjunction with the density log, but also advantageously with other logs, the caliper log gives useful information about rock characteristics as well as about the condition of the hole.

e. Flow meter -- This instrument incorporates a spinner device which, emplaced in a fixed position in a borehole, indicates the upward or downward direction of flow within the hole, and measures the rate of flow. It has been used commonly at NRTS and has provided useful data regarding vertical components of flow within an aquifer and between aquifers.

Another type of flow meter, the Tracejector, has been tested successfully at NRTS. The velocity and direction of flow between two points in a well are measured by injecting a radioactive tracer at one point and recording its arrival time at a second point.

f. Temperature log -- The logging of water temperatures in a well indicates the presence and depth of water which is warmer or cooler than the natural ground water. Such abnormal temperatures reveal the

presence of "foreign" waters introduced into the normal ground-water circulation. The log also provides temperature data for use in connection with water-resistivity logs.

g. Water-resistivity log -- Natural ground water at NRTS is very low in dissolved solids, averaging about 250 ppm, whereas introduced waste liquids are slightly more saline, with salt content in the neighborhood of 1000 ppm. Because of this chemical difference, the difference in electric resistance is a direct guide to the occurrence of "foreign" water in the aquifer. The water-resistivity log provides a convenient record of deviations from normal resistivities.

h. Specific-conductance log -- In contrast to the foregoing records, this log is produced not by downhole logging but by combining the data from temperature and water-resistivity logs. The product gives a more accurate idea of water composition than does either of the separate logs, and so provides a more reliable identification of the water.

The study of specific-conductance logs and flow-meter logs together forms the basis for the interpretation of flow in boreholes. This practice of combining several types of logs, including the lithologic and petrographic logs prepared by the geological staff, is to be commended and encouraged. The interpretation of poorly defined characteristics in logs can thus be enhanced, and obscure properties or occurrences often can be revealed or magnified.

The usage and interpretation of logs at NRTS conform to practice in oil fields, where the technique of downhole logging was developed. Our only qualifying comment is to caution against over-reliance on such logs without constant support from laboratory analyses of samples of the fluids and rocks whose properties are presumably being measured by the logs.

Many other logs are available for borehole investigations. Some of these may be useful in future geophysical studies in the Division of Reactor Development and Technology research program. Of particular interest are the suites of neutron logs and acoustic logs which are described briefly in the following paragraphs.

i. Neutron logs -- Neutron-logging devices all measure radiation characteristics of substances irradiated from a neutron source lowered into a borehole.

(1) Neutron-epithermal neutron log -- Epithermal neutron distribution is measured as a function of hydrogen (water or oil) in the formation. The main advantage is that the tool can be run at reasonable logging

speeds if a strong source and efficient counter are used. Disadvantages include the sensitivity of measurements to influences such as borehole fluid, cement condition, degree of mud filtrate, and position of the tool in the hole.

(2) Neutron-thermal neutron log -- Thermal neutrons are counted as a function of the amount of hydrogen and chlorine in the formation. The system has the same advantages as the neutron-epithermal neutron log, but salinity and porosity cannot be separated. Disadvantages of both systems are similar.

(3) Neutron-gamma log -- Gamma rays produced by capture of thermal neutrons are detected by the borehole counter. The source of these gamma rays is correlative with thermal-neutron density. If porosity is known, salinity can be inferred from the flux of high-energy gamma rays which chlorine, in particular, emits. Proper tool design permits good sensitivity for detecting chlorine through casing. A disadvantage lies in the lack of good agreement between theory and experimental data.

(4) Pulsed-neutron log -- Neutrons from a pulsed tool source interact with the formation, and the resulting thermal-neutron flux decay is determined. The slope of the decay is related to the presence of chlorine in the formation fluid. In terms of sensitivity, near-borehole effects, and instrumentation, pulsed-neutron logging is far superior to the steady-state methods. The tools are not widely available yet, and future developments may see this tool's greatest use in porosity determinations and in differentiating between oil, fresh water, and brine. The major problem at present with this tool is the presence in rock of absorbing elements such as boron, lithium, and the rare earths. These elements are believed to account for the much shorter neutron lifetimes in boreholes as compared to theory and laboratory model experiments. When these problems are resolved, the pulsed-neutron log will be the most effective "through casing" log available.

A modified pulsed-neutron tool measures decay of intensity of gamma-ray flux produced by neutron capture. The gamma-ray counting rate is related to the reciprocal of neutron lifetime in the medium being investigated. Thus, the log is a "lifetime log." The measurements are chiefly a function of chlorine in formation fluids, as with the other logs. However, near-borehole effects are small, and asymptotic decay of gamma rays occurs sooner than does decay of neutron flux. This tool is still in the developmental stage.

j. Acoustic (sonic) logs -- These tools consist of a sound source and two or more receivers spaced at known distances from the trans-

mitter. Travel time of acoustic energy (compressional wave, shear wave, tube wave) between receivers is measured. Given the travel time and assuming that the propagation path is known, acoustic velocity of the rock formation is inferred.

(1) Acoustic-velocity log (compressional wave) -- Travel time of an acoustic compressional wave is measured and velocity is calculated. Velocity logs are used to compute reflection coefficients and vertical velocity "profiles" for seismic investigation. The logs can also be used for correlation purposes. By far the greatest use of the velocity log is in estimating the porosity of subsurface rocks, once the effective stress, matrix material, and average pore size are known. The log is also used for velocity determinations in connection with seismograph surveys.

(2) Acoustic-velocity log (shear wave) -- Shear-wave travel time is measured between receivers. In certain formations (limestone, anhydrite, salt, dolomite, and well-cemented sandstone) shear-wave amplitude is larger than the compressional. Thus, with independent determination of compressional and shear-wave velocity plus density, Poisson's ratio for the rock is obtained, and all of the remaining elastic constants may be calculated. These approximations have proven to be very satisfactory.

(3) Acoustic-amplitude log -- All three waves (compressional, shear, and tube) are measured. Attenuation of low-frequency components of tube waves is dependent on formation rigidity, which in uniform lithology changes as a result of fracturing or fluid saturation. Commercial application of this type of log has been in attempting to detect fractures in open holes. The tool is sensitive to borehole centering and caliper, mud properties, hole size, and bed boundaries. Small shale stringers are not distinguished from horizontal fractures. Modifications of this logging method are used to determine the effectiveness of cement bonding between casing and the hole wall.

3. Geophysical mapping

A number of geophysical mapping techniques have been developed, primarily in petroleum exploration, for the purpose of learning about strata which have not yet been reached by the drill. All of them record physical properties of rocks which vary as the lithology varies. They are more rapid and less costly than exploration by the drill, but the data derived from such surveys can rarely be interpreted precisely or uniquely in terms of rock distribution and properties. Resulting maps, therefore, are less reliable than those constructed from data that could be derived directly from closely spaced boreholes.

Geophysical mapping is commonly the first step in the exploration of an area such as the NRTS where deep-borehole data are lacking. Under favorable circumstances the gross form and depth of a basin may be delimited by gravity and magnetic work, as attempted here. Indications of more localized rock distribution and structures may be obtained with suitably designed programs.

The geology at NRTS presents the geophysicists with particularly difficult problems. The rocks filling the Snake River depression are a complex of basalt lava flows which are massive to scoriaceous and cindery and have interbedded lenses and tongues of alluvial and lacustrine clays, sands and gravels. The sequence is thus extremely heterogeneous, both laterally and vertically, with regard to porosity, permeability, density, magnetic properties, seismic velocity - in fact all the physical properties which form the basis for geophysical exploration. The lavas and interbedded sediments were laid down in an easterly trending trough, the Snake River downwarp, on older rocks whose structures trend more or less north-south. These older rocks were folded, faulted and deeply eroded before the Snake River downwarp developed. Presumably the older structures pass beneath the downwarp approximately at right angles to its strike.

A principal object of the geophysical program, namely the determination of the depth and configuration of the basement surface on which the lava sequence was poured out, is thus complicated by the basement structural pattern. Both gravity and magnetic anomalies may reflect topographic relief on the ancient surface, or masses of rock of contrasting lithologies, or varying rock patterns in a structurally disturbed area. The variables are such that no unique solution is possible without deep-well data on physical properties of the rocks and depth to basement.

Hence the value of the existing geophysical-mapping program would be greatly enhanced by NRTS's proposed deep drill hole, especially if this hole extends into basement beneath the basalt sequence. Data from such a well would permit the definition of the basement surface for a considerable area surrounding the well. The degree of confidence in the reconstruction would, of course, diminish with distance from the well. A reasonably accurate delineation of the basement surface and its hydraulic characteristics over the entire NRTS, presumably would require a minimum of three deep wells penetrating the entire basalt sequence and going into the basement rocks far enough to give an indication of their porosity, permeability and fluid content.

a. Gravity and aeromagnetic surveys -- The operation of a gravimeter is based on differences in density between different types of rocks. A mapped positive anomaly could mean (1) the presence of a rela-

tively small mass of dense rock at a shallow depth, surrounded by less dense rock, (2) a large discrete mass of dense rock at great depth, or (3) an arched uplift which brings a deep layer of uniformly dense rock closer to the surface at the location of the anomaly. The accuracy of the interpretation depends on (1) the nature and complexity of the geology, (2) the operator's experience, especially in the type of subsurface geology that is being explored, (3) the spacing between gravimeter stations where data are obtained, and (4) the amount of subsurface data available from boreholes.

The operation of a magnetometer is closely analogous but is based on measurements of magnetic variations rather than densities. The problems in interpretation are similar. The magnetometer has the advantage, however, that readings can be made instantaneously and from a moving instrument. Consequently, techniques have been developed for making magnetometer surveys by trailing an instrument behind an aircraft. The amount of detail that can be obtained depends upon the flight altitude and the distances between traverses. In reconnaissance work excessive detail is apt to be more confusing than helpful.

Gravity and aeromagnetic surveys were conducted for AEC at NRTS in 1964, and the resulting data were added to those available from earlier surveys. Interpretations of the gravity data are complicated by the fact that the density of basalt varies widely from flow to flow and from place to place within a flow. Although basalt is generally strongly magnetic, it varies also in degree of magnetism and in direction of polarization. The final products of both surveys are contour maps. Interpretations of observed anomalies are speculative. Some faulting is suggested by the contours, but the evidence is unreliable without better control.

The densities and magnetic properties of rock specimens from adjacent areas have been determined by laboratory measurements, but deep subsurface control from the NRTS is desirable to improve the interpretations.

b. Seismograph surveys -- Seismic surveys involve the transmission of acoustic energy, usually from a near-surface explosion, downward into subsurface rocks. This acoustic or "seismic" energy is in part transmitted through the rocks and in part reflected and refracted back to the surface where the arrival times and energy characteristics may be measured. Seismic-reflection surveys are most commonly used by the petroleum industry to determine the depths and structural configuration of subsurface rocks. For technical reasons this method does not normally give good results at depths less than about 500 feet. The reflection method is not well suited to exploration of thick masses of basalt. It is especially doubtful that satisfactory results would be obtained from the highly lenticular basalts and sediments of NRTS, except possibly for study of selected local structures.

Refraction surveys can be used effectively at shallow depths to determine the thickness of sediments above the first basalt flow. It is not very likely that useful data will be obtained by this method at greater depths in this geologic setting, because the irregular alternation of high-speed and low-speed zones within the lava would give a confused seismic response.

c. Aeroradioactivity survey -- This work involves the recording of natural radiation from the earth's crust by means of an airborne instrument. The effects of any artificially introduced radioactivity would, of course, also be sensed. Because only preliminary work has been reported, the Committee is unable to comment on the results.

4. Conclusions

Throughout all of the geophysical programs at NRTS the need for petrophysical data from boreholes is obvious. The value of the interpretations is directly proportional to the amount and quality of supporting analytical data. This relation is made clear in projects where such data have been obtained. The geophysical program is still active and should be continued until the usefulness of the methods has been exhausted. Particularly, we urge the need for more geophysical-log studies of the inter-aquifer flow of ground waters, because the overall flow system is still inadequately understood.

H. Ground disposal of gaseous wastes

AEC is considering the vexatious question of handling radioactive gases that might leak from a reactor's containment shell in the event of melt-down resulting from a rupture in the internal cooling system. Among other procedures it has been suggested that the vapors released at high temperatures into the shell be pumped into a ground-water aquifer. Inasmuch as the injection would have to be completed quickly, it was further suggested that the subsurface reservoir be prepared in advance by the injection of air so as to displace an appropriate amount of water, thereby producing a huge air bubble in the aquifer.

The Committee doubts that this procedure would be practical, because over a period of time the air bubble would move along the aquifer, eventually becoming dispersed, and therefore a stream of air would have to be injected from time to time throughout the life of the plant in order to be ready for an emergency. Under unusual circumstances in which a domal structure or a lenticular formation makes a local trap, the procedure might be effective.

It has also been suggested that the zone of aeration, the unsaturated interval lying above the water table, be utilized as a receptacle for radio-

active gases. Few plant sites, however, have an aeration zone thick enough to provide a useful capacity for such injections. Moreover, such a disposal procedure for gases would be subject to the same objections as for liquid wastes -- i. e., the danger of possible migration into and along the aquifer, particularly under the influence of moving waters.

VII. OPERATIONAL PROCEDURES

In addition to the Research and Development projects described in preceding pages, the Committee has considered also some broad geologic and hydrologic aspects of other ground disposals. They pertain to practices which are in general use at the sites visited by the Committee and which are part of the whole range of disposal procedures in which geologic aspects bear heavily on the long-term safety of the operations. Attention is called to the outline of the geology of the four major plant sites where disposal techniques are being developed (pp. 14-18 of this report). Present operational procedures are considered in three categories, as determined by the levels of radioactivity in the wastes.

A. High-level wastes

Both liquid and solid high-level wastes are now being stored in underground containers built of steel and cement. The operators consider the tanks for high-level liquids as being only an interim device pending the development of safer techniques for permanent disposal. Procedures for solidification of the liquids are being developed, and it is anticipated that the tanks eventually will be used only for temporary storage during initial decay and cooling stages.

Methods for disposal of the products of solidification, like disposal of saturated or partially saturated adsorbants and of high-level radioactive trash (e. g., used laboratory equipment) remain to be perfected. If the solid product will be essentially insoluble for a period of 600 to 1000 years, and if sorbed radionuclides will not be released from contaminated solids during the same period, the solids can be stored safely at shallow depths in the ground above the water table. However, the permanence of fixation on trash or perhaps even on used ion-exchange materials cannot be relied on, and such a disposal site would still carry the hazard of accidental discovery and release to the biosphere in the event of excavation in future centuries when knowledge of the burial may have been forgotten. Storage below the fresh-water zones, particularly in salt beds, would appear to be the safer procedure for all manner of high-level solids.

B. Intermediate-level wastes

Treatment of intermediate-level wastes varies from site to site, as also does the definition of what constitutes intermediate levels. Solid trash

is buried at shallow depths in earthen trenches at all sites; radiation levels in adjacent soil are monitored in order to avoid concentrations higher than accepted safe levels, but there remains the risk of unanticipated movements of the radionuclides as changes in the chemical or hydrologic environments upset the ion-exchange equilibria.

Treatments of intermediate-level liquids by evaporation in order to reduce their volume and by ion-exchange materials to reduce their radioactivity, have been investigated, and such systems are being used. At sites in semi-arid lands the intermediate-level liquids are pumped into seepage cribs and trenches, their subsequent movements through the earth being monitored through borings. The desired objective in controlling such disposals is to avoid appearances of radioactivity in excess of a small fraction (usually one-tenth) of MPC at the nearest point of use downstream.

C. Low-level wastes

Low-level trash is buried at shallow depths. The characteristics of low-level liquids, and disposal methods, vary from plant to plant. Very large volumes of cooling water, for example, which normally has little or no radioactivity but which may occasionally receive accidental discharges of radionuclides, are generally directed into ponds, swamps, or surface streams from which they eventually find their way into the major rivers. Assuming constant monitoring which would permit the operators to direct the flow temporarily into more confined reservoirs for detention in the event of serious contamination, this procedure appears to be harmless.

Other low-level liquids at some sites are pumped through disposal wells directly into fresh-water aquifers, the operators relying on long travel times and on sorption phenomena in the aquifer to reduce the radioactivity to safe levels before the contaminated water reaches downstream points of use.

The low-level liquids contain all manner of radionuclides, most of which are short-lived. At all locations, however, some of the isotopes are long-lived, the more common ones being tritium, cesium¹³⁷, strontium⁹⁰, and cobalt⁶⁰. Not all of these are equally hazardous to man, and the degree of hazard is not directly proportional to their longevity; strontium⁹⁰ and cesium¹³⁷ are the ones of greatest concern because of both their longevity and biological hazards.

The amounts of the long-lived radionuclides that are put into the ground with low-level wastes vary from year to year and from location to location, as do the total amounts of all radionuclides. Radioactivity produced by cesium¹³⁷ and by strontium⁹⁰ ranges from a small fraction of one percent

in some places to more than 10 percent at others, for each of these isotopes. In some places tritium accounts for more than 99 percent of the released radioactivity at certain times.

At present the amounts of total activity produced by waste are kept well below RCG levels between the disposal areas and the nearest points of use which are beyond the reservation boundaries. In some cases these distances are great, and large areas of intervening land can become contaminated before measurable amounts of activity reach the producing wells or streams. Moreover, the first appearance could be the fringe of a dispersion band which would be followed later by the zone of concentration. Monitor wells are located between the disposal areas and the nearest points of use, most of them clustered around the disposal facilities, and it is at these points that the criterion of RCG levels should be applied in all cases as it is now in some.

D. Geologic factors in appraisal of operating procedures

In nearly all of the ground-disposal procedures which currently are part of routine operations, two factors are depended on for protection of the biologic environment: (1) the capacity of soil and rock to contain much of the radioactivity by sorption phenomena until decay to innocuous levels, and (2) long travel time in respect to decay time. Both factors are governed by parameters which can be and constantly are being determined empirically, both in the laboratory and in the field. At present, therefore, no serious hazards have been created by the current disposal operations.

The Committee, however, is concerned about the long-term safety of the operations if they are to be continued at the same sites for many decades or even for centuries. The ion-exchange equilibria are reversible, and under changing conditions desorption could replace adsorption. Such a changed situation might result from man's future activities which would affect the hydrologic systems in the aquifers as dams are built, irrigation is accelerated or extended into new areas, or ground-water aquifers are subjected to higher withdrawal rates, all of which are not only possible but likely happenings in forthcoming decades. Climatic changes in future centuries may also be sufficient to alter substantially the hydrology in an aquifer and thereby affect its sorption capacity.

The concept of "delay and decay" is applicable to many components of radioactive wastes, but the long-lived isotopes such as strontium⁹⁰ and cesium¹³⁷ are components whose threat is reduced hardly at all in a few decades. As the adsorbant earth materials under a disposal site become saturated after long-continued disposal of even low-level wastes, the concentration of radioactivity eventually could become equivalent to that which

would result from lesser volumes of higher-level wastes, depending upon the rate of accumulation of long-lived nuclides. In such an event the disposal concept then becomes one of "concentrate and contain," but in the event of altered hydrologic conditions the prospect of containing the concentrated long-lived radioactivity becomes dim. The movement of radionuclides in the subsurface is bound to be extremely difficult to control in the absence of unsaturated natural adsorbants.

With the above considerations in mind, the Committee is especially anxious about continued ground disposals of any level of wastes containing long-lived radionuclides unless they be emplaced below the fresh-water aquifers at such depths and under such hydrologic conditions that they will not be returned to the biosphere.

The Committee is also dubious about the concept that in arid and semi-arid lands meteoric water does not percolate downward as far as the water table but instead is lost entirely by evaporation and plant transpiration. Operations conducted under this concept are saturating tangible volumes of soils with radionuclides, some of them long-lived, which in the course of a century or two may be carried to the water table by catastrophic "once-a-century" deluges. Especially in areas having centripetal surface-drainage systems and where innumerable local topographic depressions collect runoff, contamination at or near the surface may be subject eventually to transportation downward to the water table in the event of a rare calamitous flood. The Committee is not aware of any past or present research that might aid in determining the extent of this risk. It is a field of investigation which should not be overlooked as a part of the research pertinent to ground disposals of long-lived radioactivity.

VIII. DEEP EXPLORATORY DRILLING

A. National Reactor Testing Station

At present no one knows where the base of the fresh-water system lies in the Snake River Basin. Nor is anything known about the lithology of the rocks at those unknown depths. It is important to learn as much as possible about the geology and hydrology of the deep rocks in order to understand the complete hydrology of the NRTS site as a further guide to the fate of radioactivity that is released in it.

The drilling of a deep exploratory well at NRTS has been recommended by the staff there, and we strongly support the recommendation -- including continuous coring, geophysical surveying by a number of logging devices, measurements of pressure or static heads, determination of the rates of buildup or drawdown, and collection of fluid samples at frequent intervals.

In this well as in all exploratory borings, shallow and deep, the properties of the rocks with respect to movement of fluids, and the composition of fluids, should be determined by laboratory analyses of samples rather than solely by interpretation of geophysical logs. More than one deep exploratory well may eventually be needed in order to gain the essential three-dimensional view of the deep hydrologic regimen.

The objectives cited by NRTS are desirable and necessary. If such a deep test is scheduled, NRTS may find it helpful to obtain the services of one or more geological and engineering experts who have had long experience in exploratory drilling in similar terrain in the petroleum industry.

B. Hanford Atomic Products Operation

An oil company drilled a wildcat well in the Rattlesnake Hills in 1957-1958 to a total depth of 10,655 feet, where it was abandoned as a dry hole. The drillsite is near the southwest edge of the Hanford area. At the total depth the drill was still in Tertiary volcanic rocks, and the operators reported fresh water at the bottom; however, no analysis of the water was made. We support the view of Hanford personnel that the hole should be re-entered for the purpose of sampling the fluids, obtaining pressure measurements, and running additional geophysical logs.

Nothing is known at present about the hydrologic system beneath the volcanics in the Pasco Basin, or even about the lithology. For that matter, there is little information of any kind about rock formations and their contents below a depth of about 2000 feet. The nature of the fresh-water aquifer systems in the deeper part of the volcanic series is critical to a complete understanding of the eventual fate of all foreign fluids and nuclides that are accepted by the fresh-water aquifers. For these reasons we urge that efforts be made to re-enter the Rattlesnake Hills boring and conduct necessary tests, as a prelude to any further deep drilling that may be required later.

IX. DISPOSAL VAULTS IN DESERT HILLS

It has been suggested that a tunnel or other excavation in the Rattlesnake Hills at Hanford might be a safe place for disposal of dry radioactive solid wastes. The hills rise more than 1500 feet above the surface of the Pasco Basin to the northeast, and even more above the water table. Precipitation on the hills appears to be light. A similar situation might be found at Middle Butte at NRTS. Such situations might provide suitable dry storage or disposal facilities for radioactive solids of many types, including baled trash and such objects as those which are currently stored on railroad cars in tunnels under the plains. Proponents of the idea emphasize that the chief advantage of such a site would be its elevated position where runoff cannot

collect. Care would need to be taken to protect the contents from drenching, leakage, and runoff or percolation of contaminants to the outside ground surface or downward to the water table.

However, too little is known about geologic factors in these hills to enable one to recommend any construction operations. It is necessary to know more about details of local stratigraphy, lithology and structure, especially jointing. As a preliminary measure, the hills should be mapped in detail, in order to determine the position and attitude of the thickest and least-brecciated lava flows, because sound basalt would probably hold openings that are permanent and virtually indestructible. In order to determine the feasibility of the proposal, geological studies are needed along the lines suggested.

X. GENERAL CONCLUSIONS

A. Criteria

The Committee's criteria in evaluating disposal methods are: (1) permanent isolation from the biosphere of all hazardous concentrations of radionuclides; (2) protection from long-lived radioactivity must extend for 600 to 1000 years; (3) when safety is involved, cost is secondary.

B. Costs

Lack of funds has been cited at one location or another for inability to conduct needed research or to use alternate disposal methods which are agreed to be safer than current practices. The Committee recognizes that decisions on expenditures must be based on many factors, often including some that may not be known to all staff employees. However, it is apropos to point out that waste-disposal costs are now a small part of the overall expense budget of the nuclear industries, and that any compromise with safety for the sake of economy could lead, in the long run, to a mushrooming of waste disposal into the most costly item in the use of nuclear power.

C. Evaluations

1. Progress in new techniques

The Committee is pleased with progress in methods for solidification of high-level liquid wastes, burial of high-level solid wastes in salt beds, and, as far as its present application at ORNL is concerned, the injection of grouted intermediate-level wastes into shale fractures. There are some reservations regarding the capacity of the subsurface at ORNL for continued injections of grout over periods of many decades, and this method therefore should be re-evaluated periodically.

2. Disposals to the environment

The Committee thinks that the current practices of disposing of intermediate and low-level liquid wastes and all manner of solid wastes directly into the ground above or in the fresh-water zones, although momentarily safe, will lead in the long run to a serious fouling of man's environment. Such methods represent a concept of easy disposal that has had and will continue to have great appeal to operators, but we fear that continuation of the practices eventually will create hazards that will be extremely difficult and expensive to eliminate. Although the ion-exchange capabilities of natural earth materials under disposal sites will retain quantities of radionuclides and provide a safe container for the shorter-lived ones, it would appear to be prudent to reserve a large portion of the capacity for accidental releases -- especially in humid regions where the water table is shallow and distances between disposal sites and discharge points are small.

At ORNL disposals into surface pits in a shale formation have been troublesome because of some seepages and overflows. The contaminated areas adjacent to the pits now offer a unique opportunity to study in a "field laboratory" the migration of nuclides through earth materials. Particularly the situation provides an opportunity to determine whether or not earlier assumptions regarding the permeability of brittle shales might have been erroneous, to map migration routes and rates, and to learn to what extent lithologic variations in the shale may affect calculations of ion-exchange capabilities.

At NRTS all operations are conducted over one of the largest of the country's remaining reserves of pure fresh water. In addition to present regrettable contaminations by salty wastes from irrigation and industrial effluents, contamination by radionuclides is a prospect which must be constantly guarded against. The same protection is needed for the large reserves under the Hanford site, where irrigation and dam projects are crowding upon the boundaries of the reservation. The effects of irrigation developments on the Wahluke Slope north of Hanford's "100" area, for example, should be of a matter of concern and study. Another potential hazard at Hanford involves the possible flooding of sectors along the Columbia River in the event of a landslide from White Bluffs into the lake which is to be created by construction of the Ben Franklin Dam. These are the kinds of events which in the course of future decades may substantially alter the hydrology of aquifers under the disposal sites.

These possibilities and the need to protect diminishing reserves of potable ground water strongly influence the Committee's appraisals of current and proposed waste-disposal practices. All proposals for surface or near-surface storage of calcined high-level waste products in semi-arid

regions where the "dry soil" above the water table is assumed to be a safe container, should be examined carefully in the light of possible events of future centuries. Even storage of these products in surface tanks or bins as a permanent disposal appears to be risky.

3. Problems in geohydrology

As part of the research and monitoring program, NRTS has been investigating vertical flow in wells, with the desirable objective of learning more about interflows from one basalt aquifer to another, lower or higher -- a subject of importance about which little is now known. We suggest that the effects of the extreme anisotropy of the basalt aquifers also need more adequate consideration, both at NRTS and at Hanford. Rates and direction of ground-water movement, both horizontal and vertical, should be determined as precisely as possible. We hope that the staffs at these sites will continue and extend their studies of vertical flow by means of flow measurements, in uncased holes as much as possible, and also by means of static heads measured at different depths in the same hole. We think further that trace injection and modern methods for determining borehole water movement should be put to use whenever pumps are pulled from existing wells and in all newly drilled wells. The results of monitoring the movements will be misleading if waste fluids should bypass monitoring sites. This bypassing can happen easily in ground-water systems as deep as these, complicated by the peculiar geologic features of basalt and intercalated sedimentary beds and by the prevailing hydrologic characteristics of extremely high transmissibility and extremely low storage capacity.

Further in regard to the geohydrology at the semi-arid sites in the Columbia Plateau, we reiterate our concern about the prevailing concept of the "dry soil" zone above the water table as a zone which is never completely penetrated by rain water or snow melt and which therefore is a safe container for adsorbed radionuclides. We urge that AEC arrange for continuation and intensification of field investigations to determine the amount and rate of precipitation necessary to establish percolation to the water table in various types and thicknesses of soil and rock, both at Hanford and at NRTS. A study also should be made to determine the possible extent of upward movement of radionuclides to the root zone and thence to the surface along with water which reaches the surface and is transpired or evaporated.

The Committee would like to be able to offer some suggestions for research leading to better predictability of the results of unforeseen changes in the hydrology of a disposal reservoir, but the question is not an easy one to answer. Both man-made changes such as those caused by dams, irrigation projects and increased withdrawal rates, and natural changes resulting from catastrophic floods, slower processes such as erosion and channel cutting,

or even long-term climatic changes, were considered. Continuing laboratory studies of reversible ion-exchange phenomena are desirable, but of course field studies eventually will be needed.

Probably the problem as a whole is a special case within the spectrum of "recharge" problems that are so poorly understood. Actually there is relatively little knowledge of infiltration rates and mechanisms, percolation rates, and other processes -- especially through great thicknesses of unsaturated earth materials. The suggestion is offered that AEC support fundamental research on recharge mechanisms in the environments in which disposals must be conducted. This research would involve sophisticated analyses of precipitation, runoff, soil moisture, and water-level records as well as terrain studies involving the pedology and geology of selected sites. Artificial recharge floods and tracer studies might also be involved, despite the fairly large number of such investigations that have already been carried out.

4. Deep-well disposals

The Committee doubts that the deep subsurface geologic and hydrologic conditions beneath the lava series at Hanford and NRTS are suitable for disposal of waste liquids. In April 1961 the Subcommittee on Atomic Waste Disposal of the American Association of Petroleum Geologists, in selecting provinces for study of deep-well disposal potentials, rejected all parts of the Basin-and-Range province and other regions having similar tectonic complexities, because of the likelihood of structural features that would promote the escape of radionuclides. In more stable tectonic provinces, however, the method holds much promise for the disposal of waste liquids.

Recently aroused public concern about the seismic activity that is said to result from deep-well injections of toxic liquids into crystalline rocks of the Precambrian basement near Denver, Colorado, points up the need for understanding all facets of subsurface technology in selecting disposal sites and reservoirs. Because the hydrology of basement rocks has not been studied to any appreciable extent, the Committee's recommendations are restricted to deep-well disposals in permeable sedimentary strata whose fluid mechanics are largely those of granular rather than fractured aquifers.

In view of the anticipated need for suitable new plant sites as the nuclear industry expands, development of a program of exploratory drilling in geologically acceptable basins should not be long delayed. Guidance and aid can be obtained by employing on a permanent basis geologists and engineers who have had experience in petroleum exploration. As an alternate procedure, a contract with a major oil company which has broad experience

as well as complete research and operational facilities for this kind of exploration, would be useful. As for costs, a large amount of footage can be drilled and tested with an investment of \$1,000,000 to \$5,000,000, the exact amount depending on such factors as remoteness, terrain, and the character of the subsurface lithology. Costs can be reduced by joining forces with the petroleum industry if its borings are in areas of interest to AEC. Exploratory holes in locations which prove to be suitable for waste disposal can readily be converted to operational input wells or monitor holes. In the long run, drilling and testing costs will be a small part of the overall disposal program.

As for safety, the surface equipment is no more susceptible to accidents than that which is being used for hydraulic fracturing and grout injections at ORNL. Once underground in properly selected reservoir formations, the radioactivity is permanently shielded by thousands of feet of rock, a safer and more certain disposal than some other methods that have been considered. Provided sufficient time has elapsed in temporary surface storage to permit cooling to a satisfactory degree, even high-level waste liquids of suitable quality can be injected safely into deep permeable strata, although at present the technique is being considered only for low-level liquids.

5. Bedrock storage at Savannah River Plant

Since the inception of the research project for bedrock storage at SRP this Committee has favored continuing investigation to determine the feasibility of the proposal, hoping that it would lead to a more acceptable method than storage in surface tanks. At the same time, however, the Committee has retained doubts that a permanently leakproof chamber can be constructed in the Precambrian bedrock at the plant site and that the proposed disposal method would provide complete protection against contamination of fresh-water aquifers. It was realized that the answers to these questions could come only from detailed subsurface testing in situ.

A large volume of hydrologic data has now been collected and is being studied, but the Committee is unable to agree that the integrity of the system has been proven. Still more study of the data, and further testing would be required for complete understanding of the hydrologic environments in the subsurface. The period of field research involving studies with observation wells apparently would be much more prolonged than was first envisioned, inasmuch as a totally new branch of the science of subsurface hydrodynamics is being explored. It may well require several more years of experimentation to prove that leakage from the bedrock into the overlying Tuscaloosa aquifers will not occur at some place within the basement area that would be invaded by escaped contaminants.

In its own appraisal of safety factors, SRP cites three separate "barriers" (delay factors) that, in its opinion, will protect man's environment from invasion by high-level wastes if they are emplaced in a storage chamber in the bedrock:

(1) The time required for hazardous radionuclides to migrate from the storage chamber through "sound" (unfractured or slightly fractured) rock to a major fracture.

(2) The time required for the radionuclides to migrate through a network of major fractures to a discharge point at the Savannah River.

(3) In the event that radionuclides should escape into the overlying Tuscaloosa Formation, the efficiency of natural ion-exchange agents in the aquifer and the additional time required for migration through the aquifer to the river.

The appraisal starts with the premise that the nearest point of risk is the Savannah River, assuming the presence of effectively impermeable layers between the Tuscaloosa aquifers and the surface. On the contrary, it is the Committee's opinion that the fresh-water reserves in the combined Tuscaloosa aquifers are the first points of risk, and important ones, because they are certainly going to be drawn on increasingly for human consumption in approaching decades. In the event of future heavy withdrawals from the Tuscaloosa aquifers, the increasing difference between the head in those aquifers and that in the basement system would tend to increase any flow from the basement into the Tuscaloosa which might be too small today to be discerned. The thought of using the Tuscaloosa aquifer as an ion-exchange basin, in view of the prospect that future alterations in the hydrologic system may reverse the exchange equilibria and thus release sorbed nuclides, is hardly acceptable. Contamination of Tuscaloosa water in excess of five billionths of one part per million, which is the accepted tolerance for strontium⁹⁰, would create an intolerable situation.

There is doubt and uncertainty concerning the mathematical assumptions in computing fluid movements through fractured crystalline rock. Little is known about hydrologic systems in this kind of environment, and this inadequacy in itself argues for continuation of the investigation for a long time. All that is known today about the hydrology of the Precambrian basement system beneath the Separations Plants is based on data from seven boreholes in a triangular area of about one square mile between the two plants. The only other point of control nearer than Aiken, a town 20 miles north, is the deep hole near the Savannah River in the west corner of the SRP reservation, about seven miles west-southwest of the Separations Areas. When additional wells are drilled down-gradient (the direction in which contaminants would

travel), revisions in flow estimates may be required, especially if a boring should penetrate a fault-gouge or breccia zone where flow rates may be one or more orders of magnitude higher than that of the highest previous estimate.

In view of the complex lithology of the basement rock and of the intensive deformation to which it has been subjected, the Committee doubts that all fractures at a prospective excavation site can be located in advance of digging a shaft. For that matter, the probability of escape of some of the radioactive wastes from the chamber seems to be generally accepted. The uncertainty of the prospects for locating all fractures in the vicinity of the chamber, and measuring their permeabilities, makes it difficult if not impossible to provide reliable forecasts of the travel time for migrating nuclides.

The major uncertainty in the entire feasibility study, however, is the integrity of the saprolite clay layer as a continuous impermeable barrier between the bedrock and the Tuscaloosa aquifers throughout the area of possible contamination of bedrock waters. Prerequisites to proof of the barrier's effectiveness include (1) hydrologic data from the entire area in the subsurface that might be invaded by hazardous concentrations of radioactivity, (2) correct interpretation of the data and valid computations of hydrologic parameters, and (3) elimination of the possibility of openings caused by old stream channels or by knobs or ridges in the buried Precambrian surface. Sonic (acoustic) logs which may indicate the suitability of high-frequency seismographic mapping to determine the extent of the clay layer would be desirable.

In summary, it can be seen that there is doubt that it will be possible to prove safety of the proposed bedrock-storage system for high-level liquid or soluble wastes. Acting on the views of the majority of the Committee members, and still recognizing the existence of many uncertainties, the Committee recommends that investigations toward bedrock storage at SRP be discontinued.

At the same time, the entire Committee urges against any thought of permanent storage or disposal of high-level wastes above or in any of the fresh-water aquifers at the SRP site. As the recommendation regarding bedrock disposal is based primarily on inadequacy of safeguards against contamination of the fresh waters, disposal above or directly into those aquifers is obviously even more to be avoided. Apparently the only safe disposal for high-level wastes would be an offsite disposal, presumably involving solidification before transportation.

D. Planning for the future

AEC's long-range plans for future waste-disposal procedures are being made carefully and cautiously, as befits an operation that involves increasing volumes of elusive, hazardous materials. Recognition of confining parameters in the environmental characteristics which determine waste-disposal potentials at existing plant sites provides a clear and reliable guide to some of the criteria by which the suitability of any proposed plant site must be judged.

Sites for the plants where major waste-disposal operations are now being conducted are inadequate in one way or another with respect to ground disposals of radioactive wastes. Although such shortcomings are understandable in view of the limited knowledge of disposal problems and techniques a decade or more ago, the current development of plans to make more complete use of the environment for future, more voluminous, disposals at most of the sites is noted with considerable anxiety. In light of today's more advanced, though still insufficient, understanding of the geological, chemical, and physical parameters at all of the sites, major efforts are still being devoted to on-site disposals of intermediate and low-level wastes and storage of high-level wastes, some of which methods display the character of expedients designed to make the best use of poor locations. For the future, it is hoped that either off-site disposals of calcined solids, a costly alternative involving transportation of dangerous materials, or reductions in the output of radionuclides as other processes or other plants are developed, will alleviate the situation.

In this connection, the Committee dissents from the working philosophy of some operators, although certainly not that of AEC, that safety and economy are factors of equal weight in radioactive-waste disposal, and that the relative desirabilities of disposal practices can be assessed on the basis of hazard times cost. Certainly the present problems of stream pollution by industrial and municipal wastes have arisen from the use of this philosophy in the past. The Committee remains convinced that economics is a criterion secondary to that of safety.

In considering the many restrictions that are necessarily imposed on the methods of radioactive-waste disposal, and the wide variety of geologic, hydrologic and other conditions at different sites, the Committee is especially aware of the fact that privately owned plants are handling hazardous wastes and that in the future even more such private operations will be initiated. In view of the need for tailoring the disposal methods to suit local conditions at each site, the Committee hopes that authority to regulate the disposals will continue to be vested in AEC, and that AEC constantly will exercise its responsibility to see that safe disposal practices always are followed. In

site selections as well as in subsequent operations, it is hoped that AEC will make sure that its contractors and licensees take full advantage of modern knowledge in subsurface geology and hydrology, reservoir engineering, and drilling and testing technology. A secure future in safe disposal practices demands nothing less than the best know-how that American industry has developed.

XI. RESUME OF RECOMMENDATIONS

Listed below are the recommendations that are included in the various discussions in the preceding pages. They are recapitulated here for quick perusal. For full explanations, references are made to the pages where they are discussed in detail.

A. Disposal in salt

1. Study of the effect of heat and nuclear radiation on shale interbeds is suggested. (VI-A-4)

B. Grout injections in shale

1. The methods used at ORNL should be re-evaluated periodically. (X-C-1)

2. Each site and operation must be evaluated individually. (VI-B-4, first paragraph)

3. Each prospective disposal formation must be fractured experimentally in order to determine pressure requirements. (VI-B-4, second paragraph)

4. Local conditions should be investigated and pilot tests conducted before a site and disposal formation are accepted. (VI-B-4, third paragraph)

C. Solidification of liquid waste

1. Surface storage of calcined wastes above or in fresh-water aquifers appears unwise; proposals for such handling should be examined carefully. (VI-C, fourth paragraph; X-C-2, last paragraph)

D. Ion-exchange studies

1. Saturated sorbants must be considered, and disposed of, as intermediate-level waste. (VI-D-1, second paragraph)

2. Cumulative concentrations of sorbed radionuclides in the ground need to be monitored carefully, as the distribution pattern will not be known accurately. Future alterations in the hydrologic system may desorb and move them. Precautions should be taken to avoid this risk. (VI-D-1, third paragraph; -2; -6; X-C-2, third paragraph)

3. Inasmuch as ion-exchange capacities in the ground are limited at most of the current operating sites, these sites should be reserved for accidental releases rather than used for routine disposals. (VI-D-2; -3; -4; X-C-2, first paragraph)

4. The use of clinoptilolite or other ion-exchange materials in storage basins is recommended in preference to reliance on the ion-exchange capacity of earth materials in the ground. (VI-D-4)

5. Studies of the movement of radionuclides in places where pits have leaked or overflowed at ORNL are suggested, as an opportunity to make use of a ready-made field laboratory. (X-C-2, second paragraph)

6. Operators are cautioned against overloading the safe capacity of the Columbia River by effluents from the Ringold Formation. (VI-D-5, second paragraph)

E. Bedrock storage at Savannah River Plant

1. The majority opinion of the Committee is that investigations toward bedrock disposal at SRP should be discontinued. (X-C-5, next to last paragraph)

2. High-level wastes should not be stored permanently or disposed of above or in fresh-water aquifers at SRP. (X-C-5, last paragraph)

3. A minority opinion of the Committee is that work on bedrock disposals at SRP should be continued, as follows:

a. It is necessary to develop computation methods for the hydrology of fractured aquifers, and then to re-analyze all bedrock data at SRP by this method, to replace the analyses that have been based on the hydrology of homogeneous granular aquifers. The data used in constructing the regional potentiometric map of the Precambrian basement complex likewise should be re-evaluated. (VI-E-3-b, -c; -4)

b. If justified by results of the re-analyses, new and more carefully controlled tests in existing observation wells should be conducted, using continuous recording instruments. (VI-E-3-c; -4)

c. If justified by the results of new tests in existing wells, additional observation wells should be drilled and tested at locations including, eventually, the areas down-gradient from proposed disposal sites. (VI-E-4)

d. Full use should be made of tritium-tracer testing in order to gain direct evidence of direction and rates of movement. (VI-E-3-b, last paragraph; -4)

e. Sonic (acoustic) logs should be obtained in all boreholes, from top to bottom, before casing is run. If velocity characteristics of the rock are found to be suitable, high-frequency seismographic mapping should be attempted in order to learn the thickness and distribution of the clay layer at the base of the sedimentary section. (VI-E-2, second through fifth paragraphs; VI-E-4, last three paragraphs; X-C-5)

f. In drilling any new boreholes, samples of the clay at the base of the sedimentary section should be collected and analyzed. (VI-E-4)

g. Visits to deep mines in crystalline rocks at various locations in the Piedmont province, where the Precambrian basement is at or near the surface, will provide first-hand information on the problems of water flow into and out of such excavations. (X-C-4)

h. Periodic reviews of considerations for accepting or rejecting the bedrock storage proposal will be required as new data and testing results are analyzed. (X-C-4)

F. Deep-well disposal

1. Now is the time to develop a program of exploratory drilling and testing in geologically acceptable basin provinces, in order to determine the thickness, petrography (including clay characteristics), porosity, permeability, and pressure patterns in prospective deep disposal reservoirs. (VI-F-3, first paragraph; -4; -5; X-C-4, last two paragraphs)

2. Costs of this program can be reduced substantially by participating in any contemporaneous exploratory drilling that may be under way by the oil industry in the area of interest. (X-C-4, third paragraph)

3. A requirement for a suitable disposal site is a thick layer of soft rock between the disposal reservoir and any stratum which must be protected from invasion. In general, a depth of about 3000 feet is minimum for a deep permeable disposal reservoir. (VI-F-1, second paragraph; VI-F-3, last two paragraphs)

4. It is essential to avoid disposal into any reservoir from which fluids later may be withdrawn as mineral resources; i. e., fluids such as fresh water, brines of great commercial value, and petroleum. (VI-F-3)

5. It is important also to avoid conflict with competitive disposal operations in the same reservoir. Records of pressure data should be continuously and permanently maintained in order to ensure awareness of possible conflicts. (VI-F-5, second paragraph)

6. In order to conserve reservoir space it is deemed advisable to concentrate waste liquids as much as possible before injection. Injected fluids should be chemically stable, bacteriologically sterile, and nonreactive with respect to reservoir rocks and fluids. (VI-F-3; -4, first paragraph; -5, third paragraph)

7. The disposal process must not permit access of radioactivity to the vicinity of fresh-water aquifers by leakage either within or behind the casing, or through fractures in rock strata above the disposal reservoir. (VI-F-3, first paragraph). Precautions should include preliminary test injections of nonradioactive fluids, except for tracer amounts, then surveying the hole with fracture-detecting instruments, and monitoring the bottom-hole pressures during injections of wastes. (VI-F-3, third from last paragraph)

8. Pilot injections at prospective plant sites are prerequisites to final site acceptance. (VI-F-3, last paragraph; -4, first two paragraphs; -5, last paragraph)

G. Geophysical studies at National Reactor Testing Station

1. Accurate data regarding the physical characteristics of the rock column at any exploration site should be acquired by laboratory analyses, not only before but also continuously during geophysical exploration. Without adequate control, interpretations of log and map data are apt to be misleading. Interpretations of geophysical mapping should be supported by analyses of samples taken from deep exploration holes. (VI-G-1, fifth paragraph; -3; -4)

2. The geophysical program should be continued until its usefulness has been exhausted. (VI-G-4)

H. Ground disposal of gaseous wastes

1. The proposed methods for ground disposal of gaseous wastes are considered to be impractical. (VI-H)

I. Deep exploratory drilling

1. A deep exploratory well at NRTS is highly desirable in order to obtain essential geologic and hydrologic data by coring, geophysical logging, and the collection and analysis of samples of rocks and fluids. (VIII-A)

2. It is recommended that the 10,655-foot boring that was abandoned by an oil company in 1958 as an unsuccessful exploration hole in the Rattlesnake Hills, near HAPO, be re-entered for the purpose of obtaining needed deep data from analyses of samples, fluid measurements, and geophysical logs. (VIII-B)

J. Disposal vaults in desert hills

1. Detailed geological investigations of topographic highs in semi-arid or desert regions, such as Rattlesnake Hills (HAPO) and Middle Butte (NRTS), should be conducted in order to determine the feasibility of using them for sites of storage or disposal facilities for solid wastes. (VI-C, last paragraph; IX)

K. Hydrology

1. Field and laboratory studies of the rate of movement of fluids, sorption capacities, and leaching and migration of radionuclides in rocks and soils should be continued persistently. (V, fourth paragraph; numerous other discussions)

2. Study of the movement of water in three dimensions in the saturated zone should be diligently pursued at all major sites of AEC. (IV-C; VI-G-4; X-C-3, first paragraph)

3. The movement of water, both upward and downward, under varying conditions of wetting in the zone of aeration at NRTS and HAPO should be thoroughly studied, particularly with reference to questions about percolation of rain water and snow melt to the water table. (VII-D, last paragraph; X-C-3, second paragraph)

4. It is suggested that AEC support fundamental research on recharge mechanisms. (X-C-3, last paragraph)

L. General

1. There is need for a standard classification of radioactive wastes, one based not only on the concentration of activity but also on the longevity of the nuclides in various ratios. (IV-A)

2. There is need for AEC to establish a discipline of waste disposal as a guide for private operators as well as AEC contractors. (V, last paragraph)

3. Safe disposal procedures should be established now rather than at later stages of power development. (V, fifth paragraph; X-C-2, first paragraph)

4. Present sites appear to be unsuited for ground disposals of large amounts of long-lived radionuclides. Safer disposal to the subsurface can be developed in geologic basins in the stable interior of the continent where fresh-water aquifers are separated from potential waste-disposal reservoirs by thousands of feet of layered strata. (IV-B-5, next to last paragraph; X-D, second paragraph)

5. In the general field of subsurface waste disposal, AEC and its principal contractors should exploit industrial technology in which subsurface investigation has reached high levels of sophistication. Closer liaison should be developed between waste-disposal technologists and major industrial research laboratories for technologic exchange in problems of mutual interest such as formation testing, ion-exchange, hydraulic fracturing, geophysical-log interpretation, and

fluid injection in porous rocks. (VI-B, last paragraph; VI-F-3, second paragraph; VI-F-4, second and third paragraphs; VIII; X-C-4, third paragraph)

6. No study of any of the phenomena involved in any means of waste disposal should be neglected because of lack of funds. Funds should be provided as necessary to insure a complete development of both practice and theory of safe waste disposal. We particularly call attention to the necessity for field studies. (V, third paragraph; X-B; X-D, third paragraph)

TABLE III

Stratigraphic table

MAJOR DIVISIONS	SYSTEMS	SERIES	FORMATION NAMES USED IN TEXT	APPROX. AGE (Million years)
Cenozoic	Quaternary	Recent		
		Pleistocene	Ringold	1
	Tertiary	Pliocene	Ellensburg	10
		Miocene		
		Oligocene		
		Eocene		60
		Paleocene		
Mesozoic	Cretaceous	Upper	Tuscaloosa	
		Lower		125
	Jurassic			
	Triassic			180
Paleozoic	Permian	Ochoa		
		Guadalupe		
		Leonard	Wellington	
		Wolfcamp		
	Pennsylvanian	Virgil		
		Missouri	Chanute	
		Des Moines		
		Atoka		
		Morrow		
	Mississippian			255
	Devonian			
	Silurian			350
	Ordovician		Chickamauga	
	Cambrian		Conasauga	
			Rome Sandstone	510
Precambrian	Precambrian	Precambrian		

XII. GLOSSARY OF WORDS AND TERMS USED IN THE TEXT

AAPG -- American Association of Petroleum Geologists.

AEC -- United States Atomic Energy Commission.

Aeolian -- Eroded, produced, borne, or deposited by wind.

Alluvial -- Pertaining to or composed of alluvium.

Alluvium -- Detrital material deposited by running water.

Aquiclude -- "A formation which, although porous and capable of absorbing water slowly, will not transmit it fast enough to furnish an appreciable supply for a well or spring." (Tolman)

Aquifer -- A subsurface stratum (or group of strata) of sand, gravel or other unconsolidated permeable sediments, or of indurated but porous and permeable rock, containing water. Usage is usually restricted to beds carrying fresh water in enough quantity to be a source of supply. See "Salaquifer."

Basalt -- A dark fine-grained or dense igneous rock of volcanic origin. Much of it is vesicular -- that is, it contains small cavities. In fractured basalt the cavities add to the permeability.

Basement -- That portion of the earth's crust consisting usually of crystalline rock, igneous or metamorphic, having complex structure and underlying generally unmetamorphosed, less strongly folded sedimentary rocks. In oilfield usage, the surface of the basement is the "floor" below which exploration for oil and gas is usually considered to be useless. The age of the basement rocks is Precambrian at most places, but younger rocks may be included in some regions.

Basin -- (Subsurface geology) -- A depression in a geological surface. It may or may not have a topographic expression. If caused by tectonic events which create a downwarp of the strata, it is called a structural basin. If it is a catchment area filled (or being filled) with sediments, it is referred to as a sedimentary basin. The hydrology within a basin is usually an integrated system which is controlled by the shape of the basin as well as by the character of the rocks in it. A sedimentary basin may be affected by post-depositional tectonism, in which case the integrity of the original system will have been altered or destroyed and eventually replaced by that of a new system.

- Bedrock -- (1) Solid or indurated rock underlying the surface veneer of soil and unconsolidated sediments. (2) In local usage, the basement.
- Biosphere -- That portion of the earth occupied by organisms (excluding bacteria which may live in subsurface waters at great depths).
- Breccia -- A rock composed of angular fragments of moderate or large size.
- Calcine (verb) -- To reduce to a powder, or to a friable state, by the action of heat; to heat so as to expel volatile matter from; to oxidize, as by the action of heat. (Webster's New International Dictionary: G. and C. Merriam Company.)
- Cambrian -- A division of geologic time and of a stratigraphic sequence. (See "Stratigraphy")
- Clastic -- Composed of transported fragments of pre-existing rocks.
- Clay -- A soft rock consisting of very small (less than 1/256-mm diameter) mineral fragments, particularly various clay minerals which are largely hydrous aluminum silicates. Other than the clay-mineral content and the very fine-grained texture, clay is characterized by its property of being plastic when wet.
- Cretaceous -- A division of geologic time and of a stratigraphic sequence. (See "Stratigraphy")
- Crystalline -- In rock descriptions, composed of interlocking crystals of one or more minerals. Granite, gneiss, anhydrite are examples of crystalline rocks.
- Curie -- That quantity of a radioactive nuclide disintegrating at the rate of 3.7×10^{10} atoms per second, which is approximately the rate of decay in one gram of natural radium.
- Disposal -- Putting materials away in a manner or place that renders them practically irretrievable. (See "Storage")
- Eolian -- See "Aeolian."
- Evapotranspiration -- Loss of water from the ground by a combination of evaporation and plant transpiration.
- Exposure -- In geology, a rock surface that is exposed to view, not covered by soil or water.

Fault -- A fracture in the earth's crust accompanied by a displacement of one side of the fracture with respect to the other and in a direction parallel to the plane of fracture.

Fluviatile -- Pertaining to streams or rivers.

Foliated -- Separable into thin plates, sheets, or slabs, as in slate.

Formation -- In stratigraphic geology, a sedimentary bed (layer) or series of beds sufficiently distinctive to be regarded as a unit; a subdivision of "group" or "series."

Geohydrology -- The science treating of water in the earth. (See "hydrology")

Geology -- The science which treats of the earth, in all its aspects.

Geophysics -- The science of the earth with respect to its structure, composition, and development.

Gouge -- Finely abraded material occurring between the walls of a fault as a result of the grinding movement.

Ground water (Underground water) -- Subsurface water occupying the zone of saturation (q. v.). Phreatic water.

Grout -- Thin mortar, fluid enough to be pumped, used for filling joints, fractures, etc.

HAPO -- Hanford Atomic Products Operation, southeastern Washington.

High-level waste -- See chapter IV-A.

Hydraulic fracturing -- Creation of fractures by the application of pressure through a liquid.

Hydraulic gradient -- As applied to an aquifer, the rate of drop of the total head in a horizontal direction in which this rate of decline is a maximum.

Hydrogeology -- The part of geology that is concerned with the interaction of water and the geologic framework.

Hydrology -- The science that treats of the water of the earth. Some scientists use the term with reference specifically to underground water, as distinguished from hydrography, which is applied to surface water.

Igneous rock -- Rock which was formed by cooling and solidification from a molten state. The individual mineral crystals may be microscopic in size, as in basalt, or large, as in coarse-grained granite. The rock types (granite, basalt, etc.) are determined by the texture and by the proportions of different minerals of which the rock is composed.

Intermediate-level waste -- See chapter IV-A.

Joint -- A fracture in rock, smaller than a fissure or fault and not accompanied by dislocation.

Kaolinite -- A common clay mineral; a hydrous silicate of aluminum, derived from the decomposition of aluminous minerals, especially feldspar.

Lacustrine -- Pertaining to lakes.

Lava -- Fluid rock such as that which issues from a volcano or fissure in the earth's crust; also, the same material solidified by cooling.

Lithology -- The study of rocks based on megascopic examination of samples; also, loosely, the composition and texture of rock.

Low-level waste -- See chapter IV-A.

Mesozoic -- A major division of geologic time and of a stratigraphic sequence. (See "Stratigraphy")

Metamorphic rock -- Rock which was formed in the solid state by the alteration (metamorphosis) or pre-existing rock under conditions of elevated temperatures and pressures or changed chemical environment.

Microcurie -- One-millionth of a curie (q. v.).

Millicurie -- One-thousandth of a curie (q. v.).

Mineral -- A homogeneous naturally occurring, usually inorganic and crystalline substance.

MPC -- Maximum Permissible Concentration of radioactivity, as defined

- by the National Council on Radiation Protection and Measurements. The term has been replaced by "Radioactivity Concentration Guide" (RCG, q. v.).

NRTS -- National Reactor Testing Station, near Idaho Falls, Idaho.

Ordovician -- A division of geologic time and of a stratigraphic sequence.
(See "Stratigraphy")

ORNL -- Oak Ridge National Laboratory, Tennessee.

Outcrop -- That part of a stratigraphic unit which lies at the surface. It may be covered by soil or water; if not, it is also referred to as an exposure.

Paleozoic -- A major division of geologic time and of a stratigraphic sequence. (See "Stratigraphy")

Pennsylvanian -- A division of geologic time and of a stratigraphic sequence.
(See "Stratigraphy")

Permian -- A division of geologic time and of a stratigraphic sequence. (See "Stratigraphy")

Petrography -- The description and systematic classification of rocks; it usually involves chemical analysis or microscopic examination of thin sections.

Playa -- The shallow central basin of a desert plain, in which water gathers after a rain and is evaporated.

Potentiometric gradient -- See Hydraulic gradient.

Precambrian -- All rocks and time older than Cambrian. See "Stratigraphy."

Pyroclastic -- A general term applied to detrital volcanic materials, such as volcanic ash, that have been explosively or aurally ejected from a volcanic vent; also a general term for the class of rocks made up of these materials.

Quaternary -- A division of geologic time and of a stratigraphic sequence.
(See "Stratigraphy")

Radiohydrology -- The science treating of surface or ground water which contains radioactive elements.

RCG -- Radioactivity Concentration Guide, as defined by the Federal Radiation Council.

- Recent (capitalized) -- The interval of geologic time since the end of the Pleistocene epoch, and the rocks or geologic events associated with it. (See "Stratigraphy")
- Reservoir -- A natural underground container of fluids. In oilfield usage, a deep stratum of porous and permeable rock such as sandstone or limestone.
- Rock -- Strictly, any naturally formed aggregate or mass of mineral matter, whether or not coherent, constituting an essential and appreciable part of the earth's crust. Ordinarily, any solid or coherent and relatively hard, naturally formed mass of mineral matter.
- Salaquifer -- An aquifer (q. v.) carrying saline water, commonly deeper than fresh-water aquifers.
- Sand -- Loose sediment (q. v.) composed of mineral or rock fragments ranging in diameter between 1/16 and 2 mm.
- Sandface -- The vertical cut surface of a sandstone or other permeable rock layer in a borehole.
- Sandstone -- An indurated sedimentary rock (q. v.) formed by natural cementation of sand.
- Saprolite -- Disintegrated rock, more or less decomposed, which lies in its original place.
- Sediment -- Material in suspension or recently deposited from the waters of streams, lakes or seas, and in a more general sense deposits of wind and ice. Sediment typically consists of loose and unconsolidated fragments of rock. The specific type is determined by the size of the grains or fragments (clay, silt, sand, gravel). Purists consider a sediment to be a type of rock.
- Sedimentary rock -- Indurated sediment, such as claystone, siltstone, sandstone, conglomerate, limestone. A characteristic feature of most sedimentary rocks is a layered composition, each layer being a bed or stratum.
- Series -- A subdivision of the stratigraphic sequence in a rock column.
(See "Stratigraphy")

Shale -- Laminated or fissile claystone or siltstone.

Soil -- (1) Agriculture: The loose surface material of the earth in which plants grow. (2) Geology: The surface zone or veneer of loose materials consisting of particles derived by decay or disintegration of rock and usually mixed with vegetal and animal products. (3) Waste-disposal usage: Sediments and sedimentary rocks; apparently often used to include all rock above the basement.

SRP -- Savannah River Plant, South Carolina.

Storage -- Putting materials away with the intent to retrieve them, or in such manner that retrieval is feasible. (See "Disposal")

Stratigraphy -- Study of the strata and their interrelationships in a sequence of layered rocks. Proper names apply to both time units and rock-age units. Table III (q. v.) shows major and lesser subdivisions, including all formation names that are used in the text of this report. Not all divisions are present at all locations; for example, Paleozoic strata are missing at SRP, where Mesozoic strata lie directly on the Precambrian basement.

Structure (tectonic) -- The attitude and relative positions of rock masses consequent upon deformative processes such as folding, faulting, and igneous intrusion.

Subsurface geology -- The study of rocks and their fluid contents beneath land or sea-floor surfaces by means of drilling and geophysical surveys.

Synclinal -- Formed by strata dipping toward a common line or plane, making a downward or trough-shaped flexure in folded rocks.

Tectonic -- Referring to rock structure and its external forms resulting from the deformation of the earth's crust. As applied to earthquakes, it is used to describe shocks that are not due to volcanism or to collapse of caverns or to landslides.

Tertiary -- A division of geologic time and of a stratigraphic sequence. (See "Stratigraphy")

Transmissibility -- Capability for permitting a flow of contained fluids. Statistically, permeability multiplied by thickness.



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Triassic -- A division of geologic time and of a stratigraphic sequence.
(See "Stratigraphy")

USGS -- United States Geological Survey.

Vadose -- Referring to water in the zone of aeration, above the water table.

Water table -- The surface whose elevation at each point is that of the level at which water will stand in an open hole whose total depth is just below that surface.

Zone of aeration -- The part of the earth's crust lying above the zone of saturation. Any water in the zone of aeration either is held in interstices by molecular attraction or capillary forces, or is moving downward toward the zone of saturation, and is known as vadose water.

Zone of saturation -- The part of the earth's crust in which permeable rocks are saturated with water under hydrostatic pressure (in excess of the atmospheric pressure). The water filling the interstices is called ground water.